The Relationship between Increment and Dominance in Individual Trees as a Basis for Thinning Method

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CONTENTS

Chapter 1.

Introduction

Thinning is the term given to the process of removing a proportion of the trees in an immature forest stand. It is carried out to give the remaining trees better conditions for growth and to increase the ~~total~~ useful yield, by overcoming the loss of usable material of trees which would normally die and decay through natural suppression.

Thinnings may be characterised by the method used and their intensity. The intensity of thinning is the rate at which volume is removed. The method indicates the composition of the volume removed in terms of canopy or tree classes.

Canopy classes can normally be differentiated when an even aged stand has reached the small pole stage of development.

Tree classifications usually recognise four main canopy classes, namely, dominant trees, codominant trees, sub-dominant trees and suppressed trees. Dead and dying trees are normally placed in a fifth class. The system used in this thesis is that of the Forestry Commission (Hummel, 1958) which is based aon Schadelin's classification of 1932. The classes are described as follows:

a) Dominants are the tallest trees, the crowns of which receive full light from above and some light from the sides.

b)/

b) Codominants are less tallthan the dominants, their crowns receiving full light from above but practically no lateral light.

c) Sub-dominants occupy positions below the general level of the canopy, usually having their tops free, receiving some direct light from above but practically no lateral light.

d) Suppressed trees are individuals entirely below the general level of the canopy and receiving no direct light.

Dominants and codominants together form the upper canopy whilst the remaining classes constitute the lower canopy.

Crown thinning (variously termed 'high' thinning or 'thinning from above') is that method of thinning which involves the removal of trees primarily from the upper canopy, whilst low thinning involves the removal of trees from the lower canopy. After a period of time, depending on the intensity, thinning from below may require the removal of stems of the upper canopy, and vice versa.

An index of thinning method was developed by Eide and Langsaeter (1941) which relates the mean diameter of the stems removed (d) to that of those remaining (D). A d/D ratio of less than 0.7 is considered to indicate a low thinning whilst crown and selection thinnings are represented by 0.85 - 1.00 and 1.00+ respectively.

Since any particular value of the d/D ratio can be arrived/

arrived at by differing proportions of the different tree classes, the concept is of limited value, though it can be an aid in approximate comparisons of thinning methods.

There are several variants of the crown thinning principle some of which are described in the following paragraphs.

The light crown method of thinning (L/C grade) was practically the only method of crown thinning applied in conifer stands in Britain until relatively recently, and even then its use was mainly in experiments. In this method, trees of the lower canopy other than dead trees are retained and the thinning is confined to removal of poorer dominants and some of the codominants.

A little over ten years ago, what has come to be known as the Scottish Eclectic method of thinning was evolved in the South Scotland Conservancy of the Forestry Commission. It consists of so thinning that the development of initially selected trees (originally 100/ac. per acre, and now nearer 35-50) is continually encouraged by the removal of competing stems of the upper canopy. Well formed trees of the lower canopy are retained unless interfering with the development of selected trees. The method has been fully described by Macdonald (1961,1963) and Stirling (1964). A similar approach has been used in Utah, U.S.A. (Anon.1960)

Certain methods of thinning are loosely referred to as crown thinning but are better described as "free" thinning. The Danish "Frijsenborg" thinning is one such method. In this thinning emphasis is placed on thinning in the upper/

upper canopy but a lower storey is not necessarily retained. (Moller and Holmsgaard, 1947) Another method of this type is the Danish Overgaard thinning (Bjerke and Anderson, 1956), in which thinning is done early, 15-16 years in the case of Norway spruce and repeated annually. Initially stems are removed mainly from the upper canopy but later are taken from all classes. Although this method has been practised by Juncker, it should not be confused with the selection thinning described by him, (Juncker, 1954). In this paper, Juncker describes the market conditions in which it is profitable to thin by removing almost solely, stems of the upper canopy, so that the d/D ratio is always greater than unity. This method of thinning has been adopted in U.S.A. (Dimock, 1956), and a similar approach has been used experimentally in the East Scotland Conservancy of the Forestry Commission, and in Northern Ireland where the method is termed "Cam" thinning. (Jack, 1965).

In general crown thinning is less widely practised than low thinning in even-aged conifer stands. Penistan (1960) has reported that in South Africa, New Zealand and Australia, low thinning is customary. Partly on the basis of the writers experience and partly on the evidence of thinning literature in general, it would appear that low thinning is the principal method used in Norway, Sweden, Finland, Germany and other Central European countries. France and Denmark have perhaps been most noted for their use of crown thinning methods. In Britain/

Britain a free thinning is practised though this tends towards a low thinning rather than crown in character, except in the South Scotland Conservancy where the Scottish Eclectic thinning is the principal method employed.

Thinning has been, and continues to be a much discussed subject. The fact that a variety of thinning methods can find acceptance under similar environmental and market conditions suggests that there are facets of thinning practice yet to be rationalized. However, the possibility of widely differing methods of thinning being equally sound biologically and economically, must not be discounted entirely.

The following quotations may serve to illustrate some of the thinning problems with which this thesis is concerned, and the conflict of opinion which exists regarding them.

"Sub-dominants of Norway spruce which have fallen below the general level of the canopy have an exceptional capacity for recovery. If freed in time they may develop into useful dominants within twenty years."

(Anon, For.Comm. 1951)

" Pure spruce high forests require treatment of the low type since it is not possible to maintain a lower storey for long."

(De Phillippis, 1949)

"This/

"This rooted misconception, that no small tree has a hope of survival, far less of ever becoming a useful and substantial member of the stand, stems from examples of trees left in a gap in low thinned woods."

(Macdonald, 1963)

"It has long been known that thinning in the upper storey is not applicable to spruce."

(Schaeffer, 1945)

"Foresters must not continue that deplorable process which made him remove first the small sub-dominant and suppressed trees....which have no effect on the development of the main crop.

(Macdonald, 1963)

"To achieve optimum production, a free type of thinning is required permitting the removal of trees of low efficiency or affecting the efficiency of others- such a thinning would be low rather than crown."

(Lewis, 1959)

"As small trees physiologically react as younger trees every selection thinning should have the effect of making the stand physiologically younger, thereby keeping up the increment."

(Moller & Holmsgaard,1947)

"The Scottish Eclectic thinning ..... ensures the unintemupted development of the effective crown on the selected/

selected very best, usually but not always, predominant or dominant crop trees."

(Stirling, 1964)

"Forest practitioners are understandably so inspired by the growth of big crowned trees that they are still a long way from this point of view. (that crown development can be excessive) The widespread fear of 'shrinking crown' in lightly or moderately thinned spruce is nevertheless completely unfounded."

(Assmann, 1964)

The practice of crown thinning in Scotland is currently increasing, largely in the form of the Scottish Eclectic method, which has recently been practised in the West and North Conservancies of the Forestry Commision, in addition to the South Conservancy where it is standard practice. The use of selection thinning in the East Conservancy has been mentioned previously.

The practice of any system of thinning must be justified in economic terms(and in turn) but must be evaluated from a biological viewpoint. Neither the Scottish Eclectic or the selection systems described above has yet been fully justified on either economic or biological grounds. The protagonists of the Scottish Eclectic method hold the view that while the system was conceived for silvicultural purposes, it has certain economic advantages. The revenue from early thinnings is usually greater than that of low thinning methods, on account of the larger average/

average sizes of thinnings which result from Eclectic thinning. The effect of interest on the revenue from thinnings is also considerable.

These economic attributes of the Eclectic method appear to be the principal motive for using the selection method in East Scotland.

This thesis is concerned only with biological aspects of thinning, however.

In 1954, Moller published the results of an investigation into the effect of degree (intensity) of thinning on total volume production, and concluded that within certain wide limits the average increment is unaffected by the degree of thinning. The validity of this claim has been discussed and disputed elsewhere, (Hamilton, 1964). Moller's paper was concerned with different intensities of low thinning and the question of the effect of thinning method on increment was not considered.

It is the latter question which underlies the subject of this thesis. The thesis is concerned firstly with the contribution to total increment made by the different tree classes in absolute terms and in terms of the space occupied by them. The effect of crown thinning on these features of the different tree classes is also considered. The changes in canopy classes of trees which occur over different periods of time are examined under different thinning treatments. Some contributory factors to the above subjects are discussed, and their implications with/

with respect to thinning practice are considered. Evidence has been compiled from world literature and experimental work, which should be regarded as complementary sources rather than simply for comparison.

Due to the limitations of time, experimental work has been confined to the the following:

a) The examination of increment of individual tree classes, and of changes in tree class, under different treatments. For these studies, data have been obtained from records of Forestry Commission sample plots. Only one grade of crown thinning, the L/C grade was available for research purposes.

b) A field experiment to study in detail, over one growing season, the increment of individual trees remaining after a very heavy crown thinning compared with trees in an unthinned stand.

These investigations are limited to two species, Norway spruce (Picea abies, (L.) Karst.) and Sitka spruce (P. sitchensis (Bong) Carr.). Emphasis is also placed on this genus in the literature review.

The literature review is contained in Chapters 2-6. The second chapter is concerned with the distribution of increment between the canopy classes. Chapters 3 and 4 consider the relations between crown dimensions and structure and increment. Inter-class movements of trees are considered in Chapter 5, and the sixth chapter is devoted to papers on thinning method experiments. Experimental work occupies Chapters 7 and 8, the final chapter being given to a general discussion.

Chapter 2

The Contribution of Different Tree Classes to Increment

This has been studied by a number of investigators among whom Borota (1962) investigated the diameter increment of Norway spruce as a function of the position of the tree in the stand. Increment cores were taken from 903 trees in two 68 year old Norway spruce stands. Annual diameter increment was found to be greatest in the tallest trees with greatest volumes and well developed crowns, decreasing to the smallest suppressed trees.

In an earlier investigation, Borota (1958) discussed an analysis of 29 stems of different tree classes from two Norway spruce stands, aged 50 and 60 years respectively. Diameter increment curves were established for each of the trees, showing that throughout the development of the stand, the best producers had been the pre-dominants and well formed dominants, the suppressed trees having produced least.

By contrast, no such permanent pattern was found by Liebold (1962) who investigated the relationship between growth and physiological age in 217 trees of 60-80 years old even aged Norway spruce. He noted that those trees having the greatest volume increment in the early stages of development were the same trees showing the greatest increment in latter stages. In the middle period however, an inversion of increment capacity occurred showing reversed roles of the early dominants and/

and sub-dominants.

Kozlowski and Peterson (1962) used aluminium dendrometer girth bands to determine seasonal increments of dominants, intermediates and suppressed trees of 43 year old red pine (Pinus resinosa). The experiment showed decisively that greatest cicumferential increase at breast height occurred in the dominants and least in the suppressed in one growing season.

Nyyssonen (1950) showed that over the period from 35 to 52 years in a natural unthinned pure Scots pine (Pinus sylvestris) stand, the relative increments per tree for each of four canopy classes were:

Dominants - 100%, Co-dominants - 30%
Sub-dominants - 10% Suppressed - 6%

Low thinning was shown to alter this trend only slightly. The contribution tothe tatal increment in this particular stand was 81%, 14%, 4%, and 1% respectively for the four classes.

Vanselow (1951) used Bavarian sample plot data to investigate the contribution made by the tree classes to total increment. He divided the populations of trees into five diameter groups, each of equal number. These were said to approximate to the Kraft tree classification. (Kraft's classification of 1884 formed the basis for that of Schadelin) The contributions of the groups in descending order of diameter were as shown below, in stands subject to moderate low thinning. The age range is indicated for each species.

Norway/

Norway spruce — 25-70yrs. - 48, 27, 13, 10, 2.
Scots pine - 41-73yrs. - 43, 24, 15, 11, 7.
Beech - 93-130yrs. - 35,24, 19, 16, 6.

Vanselow points out that the removal of 60% of the number of stems progressing from the smallest diameter size incurs a similar potential increment loss as removing 10% of the stems starting with the largest diameters.

Kuroiwa (1959) conducting investigations in a mixed Abies forest (A. mariesii and A. veitchii) constructed diagrams to illustrate the productive structure of the stand, synthesized from productive structures of individual dominant, intermediate, and suppressed trees. This information was gained from analyses of sample trees which were weighed in parts, i.e. trunk, branches, roots and foliage, in a series of horizontal strata. Reconstructing the strata so that the stand structure was represented indicated that the greater proportion of the photosynthetic system was found to be occupied by the dominants. In a later paper, Kuroiwa (1960b) calculated the annual weight increment of each portion (branches, roots, etc.) of several dominants, co-dominants, intermediate, and suppressed trees in the same Abies forest. He also arrived at a calculated value for net production. Gross production was obtained by calculating the rate of photosynthesis from light factors measured in the stand, with corrections for seasonal temperature changes. Annual respiration loss was calculated after the method of Boysen-Jensen. The results tabulated below indicate that by/

by either method of measurement the dominants show the greatest absolute production.

	Relative Net Production	Relative Actual Wt. Increment
Dominants	100	100
Codominants	35	43
Intermediates	11	13
Suppressed	1.1	1.5

Satoo, Negisi, and Senda (1959) working in <u>Zelkova serrata</u> (Ulmaceae) found a close connection between the current annual increment and the diameter at breast height.

Jackson and Ure (1964) assessed the increment in 'vigour classes' of 6-8 year old <u>Pinus radiata</u> by selecting on the basis of good form only, 160 stems per acre which were divided on the basis of d.b.h. into four categories of forty trees each. The basal area increment of these trees was noted over a period of 6-7 years. Increment as a percentage of initial basal area was found to be 32.7, 26.1, 24.0, 17.2 for the four categories in diminishing order of diameter at breast height.

Also working in <u>Pinus radiata</u>, Echeverria (1943) noted that diameter increment percent was greater in greater diameter classes, except in stands where very heavy thinning (removal of 55% basal area) had been carried out.

In terms of absolute increment per tree, it is clear that the greater the dominance of a tree the greater is the absolute volume increment produced.

In/

In each of the few cases where increment is expressed as a percentage of initial volume or basal area*, increase in increment is associated with increased dominance.

It is also worth noting that several authors consider diameter breast height an adequate expression of dominance.

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* N.B. There is no reason to expect that in this particular case basal area increment is not positively related to volume increment.

Chapter 3.

The Influence of Crown Dimensions on Increment

The crown parameters with which this chapter is concerned are crown volume, crown surface area, and cross-sectional measurements of crowns.

Lembeke (1956), working in even aged Scots pine took 2000 sample trees from 200 stands and found that crowns of greater volume were associated with greater diameter increment at breast height.

A close correlation between crown volume and wood volume increment in absolute terms was found by Swiedris (1960) who used 178 sample trees of Silver fir for his study. However, he found greater increment per unit of crown volume in trees of smaller stem diameters than in those of larger diameters. Similarly, he found that younger trees had a greater increment per unit of crown volume. For a given diameter class, tree with large crowns produced less than those with smaller crowns on a unit crown volume basis.

Mitcherlich (1961) also found an increase in absolute increment with increasing crown volume, working in silver fir/spruce selection forest in the Black Forest. He too, however found that the greatest increment per unit volume of crowns was not made by the trees of greatest crown size, but by those which had 'just risen from the middle of the upper strata'.

The/

The current annual increment per unit volume of crown was calculated by Kramer (1965) for each of the three low thinning grades of the Bowmont Norway spruce plots near Kelso. This was greatest in the lightest grade (B). The figures, calculated for the 5 year period prior to thinning in 1960 (at which time the age of the plots was 50 years) are as follows:

Grade	Aver.crown vol.-cub.ft.	crown vol/ acre (1000 c.ft.)	C.A.I. (H.ft.)	C.A.I./ 1000c.ft. crown
B	139.0	172	253	1.5
C	368.0	255	268	1.1
D	1705.0	353	213	0.6

The smallest crowns therefore appeared to be the most efficient at that stage.

Badoux (1939) noted in 9 out of 11 plots of beech aged 20-25 years and covering a variety of quality classes and thinning methods, that the most efficient crowns in terms of increment per unit of crown volume were those of the co-dominant trees.

In another paper Badoux (1946) reported no direct relation between the total crown volumes of the dominant trees and their current annual increment in Scots pine of different provenance, composition, and constitution. He found, however, that the current annual increment was very nearly directly proportional to crown surface area.

On the basis of investigations in mixed, multi-storied/

multi-storied stands, e.g. spruce/silver fir/beech mixtures, Magin (1959) argues that crown surface area is the crown character having the closest relationship with current annual increment, and in particular that area of the crown surface which has good light conditions which is presumably synonymous with the 'light crown' concept of Burger (1939).

In Kramer's paper of 1965, outlined above, it is notable that he also uses this parameter as a basis for measuring relative efficiency. For the thinning grades B,C, and D of the Bowmont plots, over the same period, the volume increments per 1000 square feet of crown surface area were 2.0, 1.9, and 1.8 Hopp.ft. respectively.

Weck(1944) carried out crown and increment measurements in Scots pine 150 years old, growing as standards over young growth, as marginal trees, and as reserved selection stems. He also conducted investigations in variously aged Scots pine, Norway spruce, Weymouth pine, Douglas fir, and Sitka spruce. In every case he found that size of crown surface (expressed figuratively as crown length times maximum diameter) was of primary importance in determining basal area increment.

Horizontal measurements of crowns are most frequently expressed as crown diameter. Much attention has been devoted, largely for the purposes of aerial photography, to the relations between crown diameter and diameter of the stem at breast height.

These parameters have been found to be correlated by many/

many authors including Ilvessalo (1950) in Scots pine -although he failed to find a significant correlation in Norway spruce -, in red pine and balsam fir by Wile (1964), and by Eule (1962) in Sitka spruce and beech. This relationship and the manner in which it is affected by stand density has been discussed by Bonnor (1964), Vezina (1962 and 1963) and Krajicek et al. (1961). However, though these findings are important, they are not strictly relevant to the aspect considered here, that of the relationship of crown projection, or crown diameter to current annual increment.

In the investigation previously mentioned, Badoux (1946) often found a close relationship between the area of crown projection and current annual increment in Scots pine.

Douglass (1961) calculated a tree volume/crown projection area ratio for every tree in different aged stands of Japanese larch. The 'tree volume' was derived simply from the formula - $(d.b.h.)^2$ x height, whilst 'crown area' was calculated from the square of the diameter of the crown. From the resulting distribution of these ratios, he selected those ratios which lay firstly 2.33 and secondly 3.08 standard deviations above the mean. On investigating the trees concerned in the field, they were found with few exceptions to be 'elite' trees.

Aerial photography was used by Eule (1959) to obtain crown projection measurements of 135 year old beech, and in conjunction with measurements taken on the ground he/

he found that basal area increment increased with crown projection but less than proportionately.

In a study of Norway spruce in the Bavarian foothills Schmidt (1953) states that a definite relationship existed between crown diameter and volume increment of the stem.

Kennel (1964) examined the relations of stem volume increment and certain other variables, namely d.b.h., height, crown projection, crown length/width ratio, and the 'social position' of the tree. The stands investigated were of pure Norway spruce and spruce/beech mixtures, aged 56-74 years. A notable feature of his paper is that stem increment is expressed per unit of crown projection. A multivariance analysis showed that d.b.h. and tree height were strongly correlated (positively) with increment, whilst a strong negative correlation was found with projection area. The other variables were only slightly correlated with increment.

Similar conclusions regarding the relation of crown projection area to increment are discussed by Assmann (1957) in referring to a study in oak (by R.Mayer). In two trial plots of oak aged 50 and 100 years, absolute increment within each crown class was greatest for trees with the greatest projections. In terms of increment per unit of crown projection the indication was that the trees with the smaller projections had the greater increments.

It is possible only to make general conclusions from papers/

papers which deal with a variety of species, of different ages. One feature which is indisputable is the evident increase in absolute increment with increasing size of crown, expressed as crown volume, crown diameter, projection area, or crown surface area. Expressing increment per unit volume or surface area of crown indicates that in some cases greater crown sizes are less efficient, at certain stages in the development of the stands. Since ultimately production is defined on an area basis, it seems reasonable to measure crown efficiency most effectively on the basis of units of crown projection. The only direct control of growing space which the forester has at his disposal is in the manipulation of area made available to a tree.

In the case of crown projection also, there is evidence that the more efficient crowns are those with smaller projection areas. Indeed, it is surprising in view of the conclusions reached previously regarding crown volume, that Kennel's crown length/width ratio is not more strongly correlated with increment when the obvious conclusion to be drawn from the evidence presented is that the most efficient crowns are narrow ones of maximum volume. Work by Zilkin (1960) on Scots pine aged 105-110 years, on three sites of different qualities indicated that the proportion of narrow crowned trees in the stand, and the tree height/crown diameter ratio, rose with increasing site quality, which was of course accompanied by higher productivity. An interpretation of/

of this could be that as nutrition became less limiting to maximum production, so photosynthetic efficiency became more limiting. Maintenance of production therefore required increased efficiency resulting in structural changes of the kind observed.

A purely theoretical study of crown efficiency has been produced by Jahnke and Lawrence (1965). Working with geometric models including a flat disc and cones of several heights but of equal base radius, they were able to show that cones intercept progressively more light with increased height. They also indicated that the amount of chlorophyll displayed per unit of the earth's surface can also increase greatly with vertical extension of the crown. This study takes no account of the effect of mutual shading which would exist in the case of a series of adjacent crowns. The authors point out that the degree of increased efficiency obtained by tall conical crowns of trees in forest conditions would be greater under conditions of diffuse light than in direct sunlight.

Few investigations have been carried out on the relative efficiency of crowns in different canopy classes in the terms discussed here. That of Badoux (1939) in which codominants in young beech stands were found to be most efficient in terms of unit volume has already been mentioned. Kramer (1965) found that the relative contributions made to increment per 1000 sq. ft. of crown surface area of dominants, codominants, and sub-dominants were in the ratio 100:63:5. in the B grade thinning at Bowmont. In the/

the L/C grade he found, however, that the efficiency of the sub-dominants and suppressed trees together was 40% of the dominants.

Chapter 4.

Aspects of Foliage and Crown Structure in Relation to Increment

Vanselow (1951b) investigated the relationship between stemwood increment and fresh needle weight in different ages and in three yield classes of Norway spruce even-aged forest. A sample of 331 trees was taken from stands ranging from 40 to 110 years of age. The weight of needles plus twigs was found to be directly proportional to age in all three yield classes. It was found that the same weight of needles produced greater stemwood increment in higher yield classes, and that maximum increment per unit wèight of needles accurred at the lower end of the age scale.

Senda and Satoo (1956) conducted an experiment in 40 year old Pinus strobus of various densities attained by thinning treatments. Stem volume production per unit weight of needles was found to greater in trees of the less dense plots, i.e. in trees of larger crowns.

By contrast, Satoo, Kunugi, and Kumewaka (1956) found that stemwood increment per unit weight of leaves in 25-40 year old Populus davidiana decreased with increased total leaf weight per tree. The authors suggest that the total production per unit of leaf weight is unaffected by the total leaf weight if the photosynthate utilised by the tree other than in the production of stemwood is considered.

In/

In <u>Chamaecyparis obtusa</u>, 28 years old, Satoo and Senda (1958) found, on the basis of 28 sample trees that stem wood production per tree was proportional to the total leaf weight. Stem wood production was found to be smaller in suppressed trees on a unit leaf weight basis, but no difference was apparent between dominant and average trees. Within the group categorized as 'of less than average stature', greater increment per unit of leaf weight was found with greater diameter and with greater total leaf weight.

Using similar methods of investigation in 46 year old plantations of <u>Zelkova serrata</u> (Ulmaceae), Satoo, Ngesi, and Senda (1959) found here too that the volume increment of individual trees was clearly related to the total leaf weight per tree. In fact a linear relationship was found bteween the logarithms of these variables. Part of the plantation had been thinned leaving 1273 stems per hectare as opposed to the control area stocking of 2600 per ha. The current annual increment per unit weight of leaves appeared to be higher in the plot which was not thinned. As in the previous paper it was found that dominant trees were more efficient in terms of current increment per unit weight of leaves.

Burger (1939), distinguishing between the 'sun crown' and the 'shade crown' (those parts above and below the level of maximum diameter respeotively) noted that both spruce and fir needles were larger in the sun crown than in the shade crown. Leaf surface per unit weight of needles was greater in the shade crown of/

of spruce. Later studies by Burger (1952,1953) in even aged and selection forests of spruce showed that in dominated trees, which bore characteristically shade leaves, needle numbers and needle surface area were found to be very much greater than in dominant trees per unit weight of needles. Under both even-aged and selction systems, production per unit weight of needles was greatest in the codominant trees, which produced 2-3 times that of the understorey trees. Pre-dominant trees were found to be less efficient than the codominants.

In another study in spruce, in an open 132 year old stand (112 s.p.h.) and a very dense 98 year old stand (712 s.p.h.) Burger (1939a) noted the highest weight of needles per unit volume of crown in the lowest diameter classes, though higher than average weights were obtained in the higher diameter classes. It was shown in terms of unit weight of needles, that in the dense stand the suppressed and sub-dominants were less efficient than the higher classes, whilst the medium diameter classes were most productive in the open stand.

Working in selection forests at different altitudes, Burger (1949) showed that the average weight of needles of spruce required to produce 1 cubic metre of stemwood was greater by a factor of three in a forest at 1800 m. altitude when compared with the forest at 900m. Burger again noted that the most efficient trees in terms of increment per unit weight of needles in the forest of lower elevation were the codominants which produced three/

three times the increment of the dominated trees and twice that of the pre-dominants.

Kuroiwa (1960), examining physiological functions in a stand of mixed 20 year old _Abies veitchii_ and _A.mariesii_ found that needle thickness increased with age, but that their photosynthetic and respiratory activities decreased with the age of the needles. He also noted differences in the characteristics of needles of different tree classes similar to those observed by Burger.

In another investigation in the same forest, Kuroiwa (1960b) found a relatively greater proportion of needles per unit dry weight of the whole tree in the dominants, and claimed that this factor together with the increased light was responsible for the higher productivity found in the dominant trees.

Moller (1947) studied the effect of site, age, and thinning on foliage of beech and Norway spruce, and concluded that their effect on foliage weight was minute. He noted that slightly smaller leaves were encountered with greater age, and with decreased site quality. In spruce Moller noted that trees with a given stem volume showed no loss of increment with fewer total needle weights.

In a detailed study of 40 Norway spruce in Bavaria, of differing age, site and yield class, Schmidt (1953) found that other factors being constant, stem increment increased with increasing dry weight of needles. Although a general relationship was found between needle area and stem increment, Schmidt points out that needle/

needle area and needle weight were not found to be directly related. Increment was found also to increase with increased needle length.

Stiell (1962), inquiring into the vertiwal distribution of needle weights in Pinus resinesa found that weight increased from the top downwards, remained constant for 4-5 whorls, then diminished.

To conclude, it may be said that as total weight of foliage per tree rises, increment rises. There appears to be no direct relationship, but at certain stages increase in total leaf weight seems to incur a decrease in production of stemwood per unit weight of foliage. There is substantial evidence that foliage is less efficient per unit weight, in trees of the lower canopy. This was found in Chamaecyparis, Zelkova, and particularly in Burger's extensive experiments in Norway spruce. Foliage in the lower parts of crowns bears characteristics different from those in the upper canopy. Spruce needles tend to be smaller and/or less dense, but have a greater surface area per unit weight inthe lower canopy.

Secondary points emerging from the papers discussed but which are not corroborated, are the possible increase in efficiency of needles with better site quality and with decreasing age of tree, and the increase in needle thickness but decrease in metabolism with increased needle age.

Most of the experiments concerned with the importance for production of different parts of the crown have depended/

depended on excision as the principal experimental technique.

Slabaugh (1957) pruned 105 dominants or codominants in a stand of <u>Pinus resinosa</u> to 30%, 50%, 70%, and 90% of their total height, which averaged 16 feet. After five growing seasons those pruned to more than 70% of their height were about to become suppressed by adjacent unpruned trees. Those pruned to 50% of their height were considered likely to remain dominant.

Am experiment in western yellow pine (Anon.,1944) showed that it was possible to remove three, leaving four whorls on 7 year old trees without reducing diameter increment. At 9 years the trees required 6 whorls to maintain increment.

Moller (1960) comprehensively reviewed other experiments of this kind. Several of the experiments reviewed indicated no production loss with pruning of up to one third of the crown. Not unexpectedly, the point to which trees could be pruned without loss of increment varied in different species and conditions, but there was general agreement that the lower branches contributed least to increment.

An important paper by Ladefoged (1946) describes a pruning experiment in Norway spruce. On a total of 75 trees, 21 years old, he reduced the crowns from below by removing up to 7 whorls leaving a range of from 4 to 14 live whorls. The results were observed over a period of five years, in each of which one whorl was removed

per/

per tree to keep the live whorl number constant. Height growth was unaffected by the various degrees of pruning but basal area increment was found to increase with increase in the size of live crown. Most significant reduction in increment was found with the removal of whorls in the upper two-thirds of the natural crown, and Ladefoged estimated on the basis of these experiments that the lower third of the natural crown was responsible for only 15% of the wood produced.

He also carried out interesting calculations of assimilation by various portions of the crown. Needles were weighed for every season of growth on each whorl of two trees. The weight distributions are shown in tables 1 and 2 for each of the two trees concerned.

Light measurements were taken in two 25 year old spruce in a closed patch of forest, at all relevant points within the crowns. Stafelts (1924) assimilation curves were then used to obtain representative rates of assimilation within the crowns of the two trees for which needle weight distributions were produced. The result is shown in tables 3 and 4.

It is clear that more than half the assimilation takes place in the needles of the latest growing season and about 80% in the latest two year's needles. The vertical distribution also illustrates the relative production of upper and lower parts of the crown.

Ladefoged's work on the distribution of chlorophyll in the crown of the trees sampled is reproduced in table 5.

Table 1. - Needle weight ~~dist.~~ ribution Tree No.1 (Ladefoged)

	needle weight - gms.								
whrl.	1938	1937	1936	1935	1934	1933	1932	total	%
1.	29.4							29.4	1
2.	90.3	26.8						117.1	4
3.	220.4	81.8	26.9					329.1	11
4.	313.4	215.3	107.1	28.5				664.3	21
5.	214.6	230.6	205.2	106.3	17.3			774.0	25
6.	79.2	137.9	86.0	68.1	68.1	0.4		439.7	14
7.	12.6	45.9	89.5	86.6	46.1	1.0		281.7	9
8.	2.9	15.1	49.8	59.3	49.6	3.3	1.5	181.5	6
9.	4.4	23.7	67.7	84.5	63.1	13.7	1.7	258.8	8
10.	0.9	5.7	11.1	12.7	7.8	2.3		40.5	1
tot.	968.1	782.8	643.3	446.0	252.0	20.7	3.2	3116.1	
%	31	25	21	14	8	1			100

Table 2. - Needle weight ~~distr.,~~ distribution, Tree No.2 (Ladefoged)

	needle weight - gms.									
whrl.	1938	1937	1936	1935	1934	1933	1932	1931	tot	%
1.	46.8								46.8	1
2.	154.0	46.3							200.3	3
3.	302.1	116.2	36.3						454.6	7
4.	422.5	269.5	133.3	28.8					853.1	13
5.	348.0	231.8	227.4	174.4	49.1				1030.7	16
6.	319.8	247.5	293.0	202.8	70.6	12.6			1146.3	18
7.	212.7	190.4	252.6	98.9	89.5	11.4	0.4		855.9	13
8.	181.9	193.5	250.0	219.8	127.3	34.3	2.8		1009.6	15
9.	61.0	73.2	109.4	111.5	76.4	40.0	11.2		482.7	8
10.	25.6	43.9	75.6	83.7	67.1	41.8	22.0	2.2	361.9	5
11.	1.7	3.7	8.1	12.6	13.5	11.8	7.0	1.6	60.0	1
tot.	2076.1	1415.0	1385.7	932.5	493.5	151.9	43.4	3.8	6501.9	
%	32	22	21	14	8	2	1	-		

Table 3. - Assimilation in different parts of the crown (Ladefoged)

Whorl	Growing season							$mgCO_2$ per hour	%
	1938	1937	1936	1935	1934	1933	1932		
1	100	(relative light factor)							
	6.8	(rate of assim./unit needle wt)							
	200	(total assim., $mgCO_2$/h.)						200	2
2.	100	80							
	6.8	5.2							
	610	140						750	7
3.	90	70	50						
	6.3	4.8	2.4						
	1390	390	60					1840	18
4.	80	70	50	30					
	6.0	4.8	2.4	2.6					
	1880	1030	260	70				3240	32
5.	60	40	20	20	10				
	5.0	3.9	1.2	1.8	0.8				
	1070	900	250	190	10			2420	24
6	60	40	20	15	10				
	5.0	3.9	1.2	1.1	0.8				
	400	540	100	70	50			1160	12
7.	50	40	20	15	5	3			
	4.4	3.9	1.2	1.1	0.2	0			
	60	180	110	100	10	-		460	5
8.	5	5	2	2	2				
	0.1	0.1	0	0	0				
	-	-	-	-	-			-	-
total	5610	3180	780	430	70	-		10070	
%	56	32	7	4	1				100

Table 4. - Assimilation in different parts of the crown, Tree 2.

Whorl	Growing season							$mgCO_2$ per hour	%
	1938	1937	1936	1935	1934	1933	1932		
1.	100								
	6.8								
	320							320	1
2.	100	80							
	6.8	5.2							
	1050	240						1290	6
3.	90	70	50						
	6.3	4.8	2.4						
	1900	560	90					2550	11
4.	80	70	50	30					
	6.0	4.8	2.4	2.6					
	2540	1290	320	80				4230	18
5.	80	60	50	30	20				
	6.0	4.4	2.4	2.6	2.0				
	2080	1020	540	450	100			4190	18
6.	80	60	40	30	20	10			
	6.0	4.4	2.3	2.6	2.0	0.6			
	1920	1090	680	530	140	10		4370	19
7.	70	50	30	20	20	10	5		
	5.4	4.2	2.2	1.8	2.0	0.6	0		
	1150	800	560	180	180	10		2880	13
8.	60	40	20	20	10	5	5		
	5.0	3.9	1.2	1.8	0.8	0.1	0		
	910	750	300	400	100	0	-	2460	11
9.	50	40	15	15	5	3	2		
	4.4	3.9	0.8	1.1	0.2	0	0		
	270	290	90	120	20	-	-	790	3
total	12140	6040	2580	1760	540	20	-	23080	
%	53	26	11	8	2	-	-		100

Table 5. - Distribution of chlorophyll, mg/gm needle wt.

whorl	needles of year- 1938	1937	1936	1935	1934	1933
1.	5.5					
2.	4.7	4.5				
3.	4.7	4.0	3.7			
4.	5.1	3.5	3.4	2.5		
5.	4.8	3.2	2.2	2.2	1.8	
6.	3.9	3.2	2.8	2.0	1.9	1.8
7.	5.1	2.3	2.3	2.1	2.1	
8.	4.5	2.5	1.7	2.0	2.1	
9.	3.7	2.0	2.1	1.9		
10.	3.1	2.7	2.0	0.7		

....

Helms (1964) measured net assimilation in Douglas fir crowns using a Hartmann-Braun infra-red gas analyser. Branchlets were sampled on the south side of trees at comparable points , two thirds of the length of the natural crown from the lowest live branch. Of the treatments he applied to trees analysed, two are particularly relevant to the subject of this chapter. Two trees, a dominant 75ft. in height and a codominant of 60ft. were pruned from below, reducing their crowns from 30 and 25ft. to 15 and 12ft. in depth respectively. No change in net assimilation was recorded in the dominant tree, but in the codominant the foliage showed considerably increased activity. Another tree was both pruned and decapitated such that only two live whorls remained. These/

These showed exceptionally vigorous activity after treatment. Possible reasons suggested for these occurences are that mineral deficiency is alleviated and water availability is greater with the redúction of transpirational surface. Dendrometer girth bands on the pruned trees indicated a net loss of production despite the greater activity of the remaining foliage.

One very clear feature is evident from the literature. It is that the lower branches contribute relatively little to the increment of the tree. In some cases increment loss through the removal of lower live branches has been imperceptible, and Mitcherlich (1961) suggests that in theory removal of the lowest branches should increase production. Echeverria (1943) claims to have found this to be the case in P.radiata in Spain.

Ladefoged's paper suggests that production in spruce crowns may take place predominantly in an external sheath constituted by the most recent two years needles.

Chapter 5.

The Movements of Trees between Canopy Classes

An impotant consideration in thinning practice, particularly in crown thinning, is the tendency of trees of different canopy class to change their relative positions as the development of the stand proceeds.

Flury's (1903) investigation of the movements of tree classes was possibly the first of its kind. He found in a B-grade Norway spruce thinning plot that in 8 years 67% of the original dominants had moved down at least one and as much as three classes, and 96% of the trees which were sub-dominant at the end of the 8year period had originally belonged to the dominant and co-dominant classes.

Gutman (1926), distinguishing between pre-dominants and dominants, found that over a period of 12 years in A-grade Norway spruce, 23 out of 43 predominants maintained their position, 19 becoming dominant, and 1 codominant. Of 141 dominants, 101 remained so, 2 moved up, 32 moved down one class and 6 moved down two classes.

Yet again in Norway spruce Zimmerle (1940) working in a 32 year old stand examined ~~the~~ movements in a series of three thinning plots over the period 1907-1938. The subsequent positions of the original dominants and co-dominants after this period are indicated below.

A notable figure here is the percentage of codominants which became dominant.

Table 6 - Present distr.bution of orig.inal doms. and co-doms.

	% of dominants			/ % of codominants	
Thin.grade	A	B	C	C	D
Removed	28	24	26	98	89
Dominant	52	51	59	0	2.92
Codominant	16	16	12	0.28	2.43
Sub-dominant	4	8	3	1.13	4.87
Suppressed	-	1	-	.57	.49

Guillebaud and Hummel (1950), from whose paper the above literature abstracts have been taken, used data from 6 pairs of plots of the Forestry Commission Research Branch to examine tree class movements. The species concerned were Norway spruce, Sitka spruce, Scots pine, Japanese larch, and two series of Douglas fir plots. Of each pair one was a B-grade thinning plot, the other either a C or a D-grade plot.

They were observed over a period of 15-25 years, during which they were thinned 4-8 times. This experiment will be discussed later and it will suffice to mention here the general points.

The conclusion was that a general downward movement takes place, so that with increasing age an ever larger proportion of the growing stock consists of trees which were originally dominant. Most or almost all of the original sub-dominants are found to have been removed by the end of the period. In three plots only, a tiny fraction of about 2-4% have become codominants. Of the original/

original codominants, an average of about 6% have become dominants, 10-15% remained as codominants, and the remainder have either been removed or have become sub-dominants.

Tree class movements were observed by Warrack (1952) in Douglas fir over a period of 20 years, commencing when the stand was 19 years old. Plots of three treatments, a low thinning, a crown thinning and a control area in which stocking was reduced to 14%, 9% and 25% respectively after 20 years, were used in the investigation. There is no definition given of the crown thinning used, but from the data given it would appear to be more of a free thinning in character. No difference was observed between the plots in the general movements of trees. In the crown thinning plot which is typical of all three, 23% of the trees changed their status in the first 10 year period. Of 14 dominants, 9 became codominant and 5 intermediate. One codominant became dominant, 2 became suppressed, and 12 became intermediates. There were 25 intermediates which became suppresed trees. In the second ten year interval, 3 trees moved up and 22 moved down.

Abell (1954) maintains that initial dominance in a young stand is not always persistant and that initial 'sprinters' may be overtaken by others, but he gives no experimental evidence to substantiate this.

Kantor (1949) followed up a similar claim made by Konsel (ref. unknown) that early dominance is not

a/

a permanent feature. Working in 17 year old spruce, 5 plots were chosen and 100 trees in each (200 in one) were measured. Three classes were defined on a statistical basis; the 'over-levels', presumably approximating to the dominant category, consisting of those trees greater than (m + u) in height, where m = mean height and u = the standard deviation. The 'Level' trees were those within the height range (m + u) to (m-u), and the 'under-levels' were those less than (m - u). The results showed that over a period of 12 years (1936-1947) approximately 50% of the intermediates remained so.

The most striking feature of the results is that only 28% of the 'under-levels' remained in that class, whilst the remainder reached the intermediate class. Kantor concluded that the 'over' and 'under-level' classes were most labile.

Nyssonnen (1950) has given details of class movements of three pairs of sample plots of Scots pine on different site types. The relevant sections of this study are given in tables 7,8, and 9.

The trend here is again for stems to move down through the classes with time. In every plot there is evidence of a relatively small number of stems moving up one class but never two. The proportions of such stems are no greater in the (low) thinned stands than in the unthinned stands. Indeed, the only plot in which suppressed trees have moved to a higher class has not been thinned.

The picture which emerges from the literature on this subject/

Table 17.-Canopy class changes in Scots pine plots, Calluna site

Class at 94yrs	natural 1	natural 2	natural 3	natural 4	thinned 1	thinned 2	thinned 3	thinned 4
stems/ha. at 94yrs.	1180	274	207	333	892	32	4	-
class at 99yrs.	% of stems/ha. at 94 yrs.							
1.	85	-	-	-	88	-	-	-
2.	14	43	-	-	10	50	-	-
3.	-	49	58	-	-	50	-	-
4.	-	3	39	90	-	-	-	-
r	1	5	3	10	2	-	-	-
stems/ha. 99yrs.	1007	267	240	386	616	28	4	-
cl.at106yrs/	% of stems/ha. at 99yrs.							
1.	94	3	-	-	95	-	-	-
2.	1	94	-	-	4	86	-	-
3.	-	3	86	5	-	14	100	-
4.	-	-	3	73	-	-	-	-
r	5	-	11	22	1	-	-	-
stems/ha. at 106yrs	948	266	233	287	484	36	-	-
cl. at 116yrs.	% of stems/ha. at 106yrs							
1.	89	-	-	-	106	111	11	-
2.	1	70	-	-	-	89	-	-
3.	-	7	74	-	-	-	-	-
4.	-	-	-	68	-	-	-	-
r	10	23	26	32	-	-	-	-

"r" denotes the percentages of trees which are dead or have been removed.

Table 8. - Canopy class changes in Scots pine plots, Vaccinium

Orig. cl.	natural 1	natural 2	natural 3	natural 4	thinned 1	thinned 2	thinned 3	thinned 4
Stems/ha. at 45yrs.	1848	693	560	308	1732	188	8 8	20
cl. at 50yrs	% of stems/ha. at 45yrs.							
1.	57	-	-	-	66	-	-	-
2.	40	29	-	-	30	70	-	-
3.	1	56	40	-	-	17	50	-
4.	-	1	7	39	-	-	-	80
r	2	14	53	61	4	13	50	20
S/ha at 50yrs	1057	945	616	168	1144	608	20	-
cl. at 57yrs	% of stems/ha. at 50 yrs.							
1.	92	7	-	-	92	3	-	-
2.	5	62	-	-	8	83	-	-
3.	-	20	35	-	-	10	60	-
4.	-	-	13	42	-	-	-	-
r	3	11	52	58	0	4	40	-
St/ha. 57yrs.	1043	637	406	147	976	472	32	-
cl. at 66yrs.	% of stems/ha at 57 yrs.							
1.	93	2	-	-	94	2	-	-
2.	6	77	9	-	6	93	12	-
3.	-	3	48	-	-	3	88	-
4.	-	-	-	29	-	-	-	-
r	1	18	43	71	-	2	-	-

Table 9.- Class changes in Scots pine plots, Oxalis-Myrtillus.

Orig. cl.	natural 1	2	3	4	thinned 1	2	3	4
Stems/ ha. at 35yrs.	2170	1015	1309	322	1446	354	66	-
cl. at 42yrs.	% of stems/ha. at 35yrs.							
1.	89	6	-	-	89	10	-	-
2.	3	76	1	-	6	63	-	-
3.	-	12	33	-	-	12	64	-
4.	-	-	-	4	-	-	-	-
r	8	6	66	96	5	15	36	-
stem/ ha. at 42yrs.	1981	847	560	14	1218	174	48	-
cl. at 52yrs.	% of stems/ha. at 42 yrs.							
1.	46	-	-	-	72	-	-	-
2.	35	6	-	-	19	41	-	-
3.	5	36	6	-	-	31	75	-
4.	-	-	1	100	-	-	-	-
r	14	58	93	-	9	28	25	-

subject is that as stand development proceeds in low thinned or unthinned stands, there is invariably a progressive downward movement of trees from one class to another. Under these same treatments, a very small but not insignificant percentage of trees are found to move upwards in canopy class. The exception to this conclusion is the evidence supplied by Kantor, which cannot be explained from the experimental evidence given.

Undoubtedly the greatest shortcoming of the literature on this subject is the lack of observations of tree class movements in stands which have been thinned predominantly in the upper canopy.

Little has been written on the general response to release of sub-dominant and suppressed trees under the conditions prevailing in crown thinned stands. A number of papers however, are concerned with the same subject under different conditions.

Hatcher (1964) investigating the growth of advance growth Douglas fir after logging, noted that younger and smaller seedlings responded faster and better to release than older and taller seedlings. A direct relationship existed between seedling height growth before release and height growth subsequent to release.

Mitcherlich (1961) remarked on the extreme resistance to suppression of some trees, on the basis of studies carried out in the Black Forest in selection forests. He found that a silver fir of 5cms. d.b.h. could be 76-122 years/

72-122 years old, and he also noted a sharp limit to the age of suppressed trees at about 170 years. This raised the question of the effect of the length of suppression on growth subsequent to release. He therefore sampled several dominants, classified them according to the age taken to reach 7cms. d.b.h. and explored their subsequent progress. This was shown to be independent of the period of suppression.

Reynolds (1952) described how virgin fellings around 1915 in Louisiana and Arkansas left large areas of shortleaf and loblolly pines under 12 inches d.b.h. These unmerchantable trees had been suppressed for 20-50 years. A sample of 50 stumps of recently felled trees showing this degree of suppression were taken at random. On average the suppression period was 40 years, during which diameter growth was 1.4 inches for every ten years. Subsequent to release, 4.2 inches diameter growth per ten years was recorded, illustrating the capacity of the trees to respond, even at this age.

In a study in two selection forests, Schutz (1964) found that the relative increment of trees after release from various periods of suppression, was greatest after 10-20 years suppression in Norway spruce, and 40-80 years in the case of silver fir. These results were not examined statistically and they may barely be significant. The investigation, conducted on 336 silver firs and 86 Norway spruse, also showed that the relative increment after release of trees suppressed up to 140 years in the case of silver fir showed no/

no appreciable loss of increment relative to trees never suppressed.

These papers tend to suggest that a period of suppression in certain conifers does not diminish the growth potential of the tree, but may, as in the opinion of Schutz, increase it.

Chapter 6.

Crown Thinning Experiments

There are relatively few thinning experiments in the literature which are concerned primarily with thinning method rather than intensity.

Vuokila (1960) has descibed a thinning method experiment in two sample plot series of Norway spruce. In all there were five plots, a heavy low and a heavy crown thinning in each series, plus one (unthinned) control plot. These plots, established in 1932 when the stand was 32 years old had been measured 6 times. Very minor differences in site qualities were then apparent, and if anything were said to favour the crown thinning plots. The plots were 0.1 - 0.25 ha. in size. Approximately the same intensities of thinning were applied in each treatment though the differences in terms of average sizes of thinnings were less than could be expected from their descriptions. The volume productions of the crown thinned plots were, after 28 years. 3% and 9-10% less than the low thinned plots in the respective series, taking site and initial stocking differences into account.

A series of Scots pine thinning experiments in Finland (the Storsjo sreies) have been described by Wiksten (1961). Three treatments were applied, namely, a heavy low thinning, a heavy crown thinning and a control which was unthinned. Established in 1903 when the stand was 52 years old, the plots had been thinned at 5 year intervals/

intervals, so that 11 thinnings had been done by the time of final assessment. The d/D ratio of the crown thinning was never greater than unity, and the first two thinnin gs in this plot were in fact low thinnings. After a period of 54 years the crown thinned plot had produced 6% less stem volume increment than either the low or naturally thinned plots.

Carbonnier's paper of 1954 on the Tonnersjoheden plots in Sweden is often referred to in thinning literature. These plots, five in all, were established in Norway spruce of plantation origin ranging from 31-40 years of age at the time of establishment. Thinnings had been conducted at 5 yearly intervals in the plots. It is apparent from the data that one of the seies must be rejected for reasons of site irregularity and pre-treatment volume differences. Of the remaining series, only three contain crown and low thinning comparisons. Details of production are given in Table 10.

Table 10.

Ser.	thin. method	ht. @ 63yrs. (m.)	init. vol. (m³/ha.)	totl. final vol.	diff.	period yrs.
1.	crown	24.0	235	834	599	32-78
	low	25.2	249	895	646	32-78
2.	crown	23.7	205	807	602	31-71
	low	23.1	202	822	620	31-71
3.	crown	29.5	340	748	408	38-63
	low	28.3	316	735	419	38-63

Diagrams showing the d/D ratios indicate that seldom is this ratio greater than unity. Initially this ratio is greater in the crown thinned plots but latterly the ratio has the greater values in the low thinning plots. Table 10 indicates the greater production of the low thinned plots.

The Norway spruce thinning plots at Bowmont (Mackenzie 1962) contain three low thinning grades plus an L/C grade, each of which are replicated four times. The average mean annual increments for the plots after 30 years treatment, at age 50 years, are:

B	C	D	L/C	
147	158	158	153	(H.ft/ac.)

However, a clearer picture of the trend can be obtained from the table of periodic mean annual increments for each five year period since the start of the treatments.

Table 11. - P.M.A.I. of Bowmont Plots (H.ft./ac.)

Period	B	C	D	L/C
1930-35	167	195	205	183
35-40	200	218	276	246
40-45	190	170	214	215
45-50	184	246	221	237
50-55	257	287	274	258
55-60	253	268	213	206

The changing pattern in the increment differences emerges from the above table. Early thinnings by the L/C method/

L/C method are shown in common with the heavy low method to be superior in production to both moderate and light low thinnings. With the passage of time, however, this trend has been reversed and the latest assessments show that the L/C method is losing ground to the B and C grades, both of which must be expected to overtake the L/C thinning in terms of M.A.I. eventually, if the trend continues as at present.

Assmann (1961) has discussed a crown thinning experiment at the Wurttemburg Research Station in Germany. Here, B and C grade low thinnings are compared with three types of crown thinning. The crown thinnings have in common the principle of selecting good dominants as future main crop elements. The mean annual increments of the plots after 30 years of treatment, at age 57 years are tabulated below.

Table 12 - M.A.I. of Wurttemburg Thinning Plots (m^3/ha.)

	low thinning		crown thinning		
	B	C	1.	11.	111.
	28.0	25.4	22.5	23.2	25.9
% B	100	91	80	83	92

The thinning method in 1. and 11. has required the removal of predominantly upper canopy trees, leaving a few 'efficient' intermediate and understorey trees. In 111. the weakes upper canopy trees and the lower storey trees have been removed.

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In this experiment also, therefore, the conclusion to be dramn from the reults is that crown thinning is less productive than lowsthinning.

Smithers (1957) compared the effects of crown and low thinning in Pinus contorta and concluded that a loss of production was incurred by crown thinning, though the data given suggests that this conclusion is barely valid.

Moller and Holmsgaard (1947) have reported the results of an experiment in Norway spruce designed among other things to investigate the influence on volume production of selection thinning, low thinning and 'Frisjenborg' thinning. The selection thinning was done on a systematic basis by which the d/D ratio was always greater than unity. Three plots of each treatment were laid out as in accompanying diagram.

S	F	L
L	S	F
F	L	S
A	B	C

The gross production of each plot over the period 1933-45 (30-42yrs.old) was as shown below.

Table 13 - Gross production, 1933-45, (cub.m.)

Thinning	A	B	C	Average
Low (L)	296	275	275	282
Frisjenborg(F)	275	296	276	282
Selection (S)	294	293	315	300

The authors conclude that while there are no significant differences in production, the experiment does indicate at least that there is no loss of production through selection thinning.

Lewis (1959) has produced data for two Danish experiments in Norway spruce involving selection thinning. One, at Mortenstrup, has shown that at 45 years the mean annual increments of a crown thinned plot and a selection thinning plot were 104% and 107% respectively of that of the low thinned plot. The other experiment, at Nodebo, consists of a comparison of moderate low thinning and selection thinning. In this case, at 45 years the M.A.I. of the selection thinning was 89% of the low thinning.

Finally, Badoux (1939) found greater production with crown thinning in two out of three series of beech plots.

There are several difficulties which arise in attempting to draw conclusions from the experimental evidence presented. Firstly, it is difficult to separate the effects of thinning method and intensity on production. The accuracy and methods of measurement are generally unknown. Species, site, climatic, and perhaps most important, age differences must be considered.

There may appear at first sight to be contradictions in the literature presented. The Bowmont plots, which are as reliable as is known, suggest that the trend in increment in the different thinning grades alters with the passage of time. Assmann (1964) has used the Bowmont data in support of his claim that in the course of a rotation/

rotation, which by German standards is normally 80-100 years at least, crown thinning is less productive than low thinning generally, the difference becoming more apparent towards the later stages of the rotation.

When age is taken into account in the assessment of each experiment then there is substantial evidence that the above opinion of Assmann is valid in the literature described in this chapter.

Summary of Conclusions from Chapters 2-6

1. Absolute increment per tree increases with dominance.
2. Increment percent rises with increasing dominance.
3. Absolute increment rises with increasing crown volume, crown surface area, and crown projection area.
4. Beyond certain ~~undefined~~ stages of development, which cannot yet be defined an increase in total crown volume or crown surface area is accompanied by decreasing increment in terms of unit crown volume or surface area.
5. Projection area is similarly found to be negatively related to increment per unit of crown projection, beyond a certain stage of development.
6. There is a suggestion that the most efficient crowns are deep, narrow, and conical.
7. As the total weight of foliage per tree increases, absolute increment does likewise, though stemwood increment per unit weight tends to decrease with increased total weight of foliage beyond an undefined point of development.
8. Foliage is less efficient in producing stemwood increment per unit weight in trees of the lower storey.
9. Lower branches of crowns contribute a relatively small amount of the total increment of the tree.
10. Foliage of the lower crown, and of trees of the lower canopy tends to be smaller, and/or less dense and has greater surface area per unit weight.

11. Some evidence is presented which suggests that in a Norwayspruce crown, the bulk of photosynthesis takes place in the most recent two year's needles.
12. As development proceeds in unthinned or low thinned stands, there is invariably a consistent, and progressive downward movement of trees from one class to another, and an ever increasing proportion of the maincrop consists of trees which were originally dominants.
13. A very small percentage of trees in these stands were observed to move up one class.
14. A few investigations have shown that the increment performance of a tree subsequent to its being released from the suppressed state, is no less than that of a tree never suppressed.
15. The majority of thinning method experiments suggest that crown thinning is less productive than low thinning, this becoming more evident towards the end of the rotation.

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Chapter 7.

Tree Class Movements and Increment Studies in L/C and C-D Grade Thinning Sample Plots

For these studies, data has been obtained from records of Forestry Commission Research Branch sample plots. Nine plots have been used, eight of which consist of paired plots, containing one L/C grade thinning plot the other a C, C/D, or D grade thinning plot. The latter are grades of low thinning (Hummel et.al.,1958). Details of the plots are given in the following table.

Table 14. - Forestry Commission sample plots

Location	No.	Species	Thin. grade	Yr.of plant.	Top ht. 1st.thin.	Q.C.
Ae	S152	Nor.spr.	L/C	1928	36.5ft.	I
Ae	S155	Sit.spr.	D	1928	33.0	IV
Ae	S154	S.S	L/C	1928	33.0	IV
Bennan	S162	N.S	D	1926	36.5	I
Bennan	S163	N.S	L/C	1926	39.0	I
Inverliever	S118	S.S	C/D	1924	37.5	II
Inverliever	S119	S.S	L/C	1924	38.5	II
Glen Duror	S126	S.S	C-C/D	1924	41.5	III
Glen Duror	S125	S.S	L/C	1924	42.0	III

Two aspects of the different types of thinning have been considered; the trends of movements of trees between canopy classes, and the increment of individuals of the different canopy classes.

1. Movements of trees between canopy classes

The classification of all trees is carried out regularly in Forestry Commission sample plots. In the case of thinning plots, this coincides with thinning operations which until now have generally been conducted on 3-4 year cycles. Trees are classified as previously defined into the dominant, codominant, sub-dominant, suppressed, and dead and dying* categories. Trees in each sample plot are individually numbered, so that it is possible to trace the development of any tree over the period during which classification has been carried out, except where it has been removed in thinning during the intervening period. It must be stressed that this classification describes only the relative positions of the trees in the stand, and these are recorded according to the classifier's judgement. No absolute measurements are involved. In all plots, the first classification was made at first thinning (at top heights, i.e. the mean height of the largest 100/ac. of 33-41½ft.).

Tree movements over periods of 14-17 years from first thinning have been traced. In most cases this includes the most recent assessment, except for plots S118 and S119, where serious windblow precluded their use. Plot S126 has/

*Dead and dying trees are considered here to be one canopy class below suppressed trees. Whilst this is not strictly true, it was found that with few exceptions such trees were previously suppressed trees.

has also suffered from wind damage in recent years.

The compositions of the plots in terms of numbers of trees of each class before and after thinnings have been plotted graphically and are shown in Figs 1-5. Tree numbers are expressed on an acre basis. Vertical lines illustrate removal of trees through thinning. Lines other than vertical indicate the change or otherwise in composition occurring between successive thinnings. In any one class a net change in the numbers of the class is indicated by divergence or convergence of the lines delimiting that class. The uppermost line is normally horizontal, but where it is found to slope some loss of trees has occurred through windblow or other accidental damage.

The position of trees still remaining in each plot at the end of the 14-17 year period have been tabulated in Table 15. They are further arranged into the classes into which they were placed at the beginning of the period. For example, of those trees in Plat S162 originally classified as dominants, 136 have been removed, 68 have remained dominants, 20 have become codominants, and 5 sub-dominants.

Whilst Figs. 1-5 show the overall changes in the proportions of classes at the end of 3-4 year periods, Table 15 demonstrates the effect of a longer period on individuals.

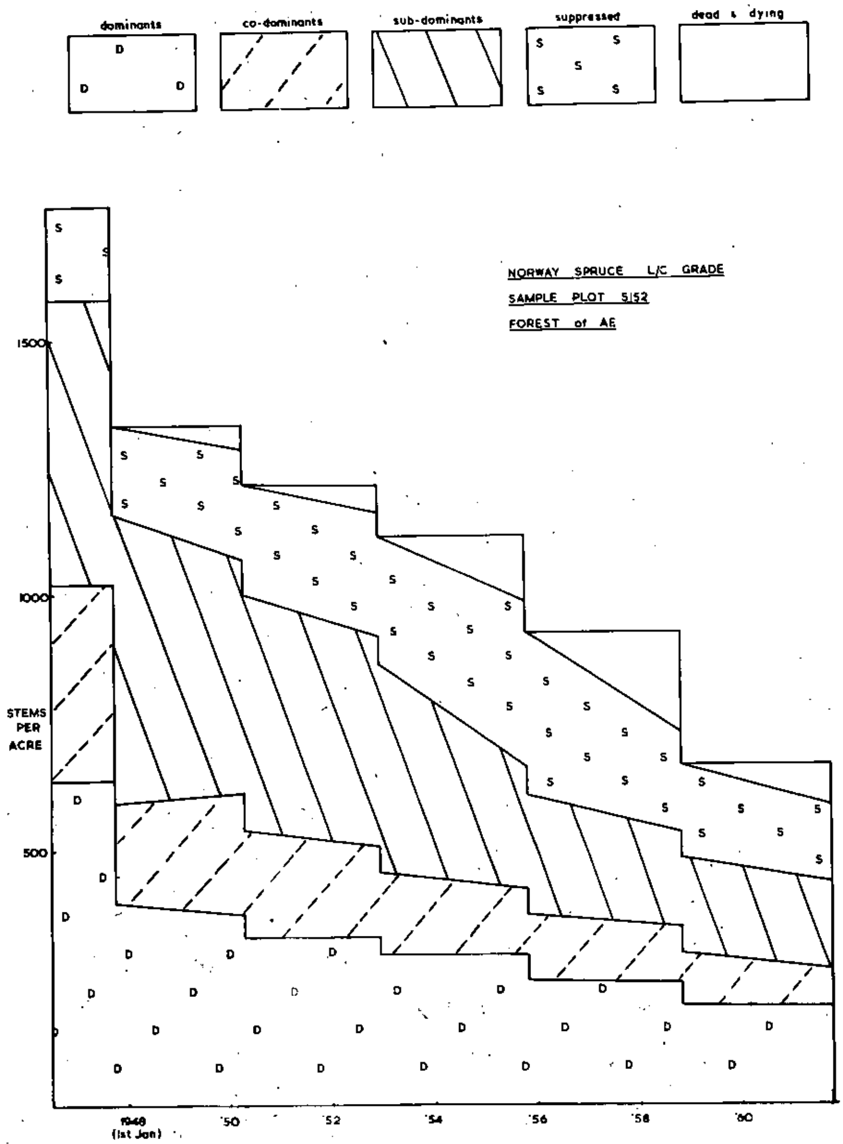
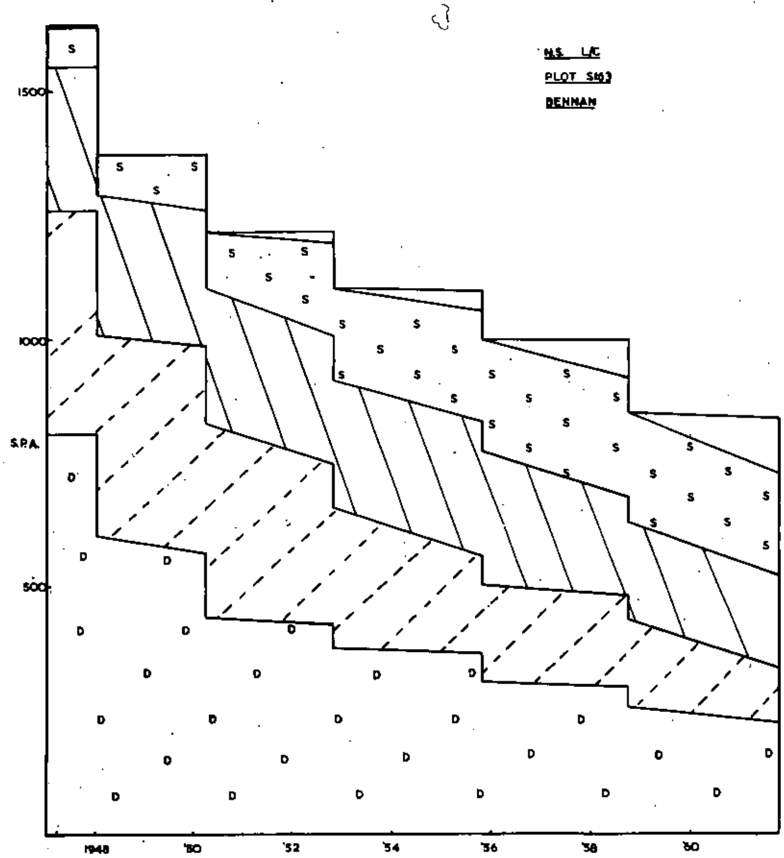

dominants
co-dominants
sub-dominants
suppressed
dead & dying
NORWAY SPRUCE L/C GRADE
SAMPLE PLOT 5152
FOREST of AE
STEMS PER ACRE
1500
1000
500
1948 (1st Jan)
'50
'52
'54
'56
'58
'60

Fig. 1


N.S. L/C
PLOT S163
BENNAN
1500
1000
S.P.A.
500
1948
'50
'52
'54
'56
'58
'60

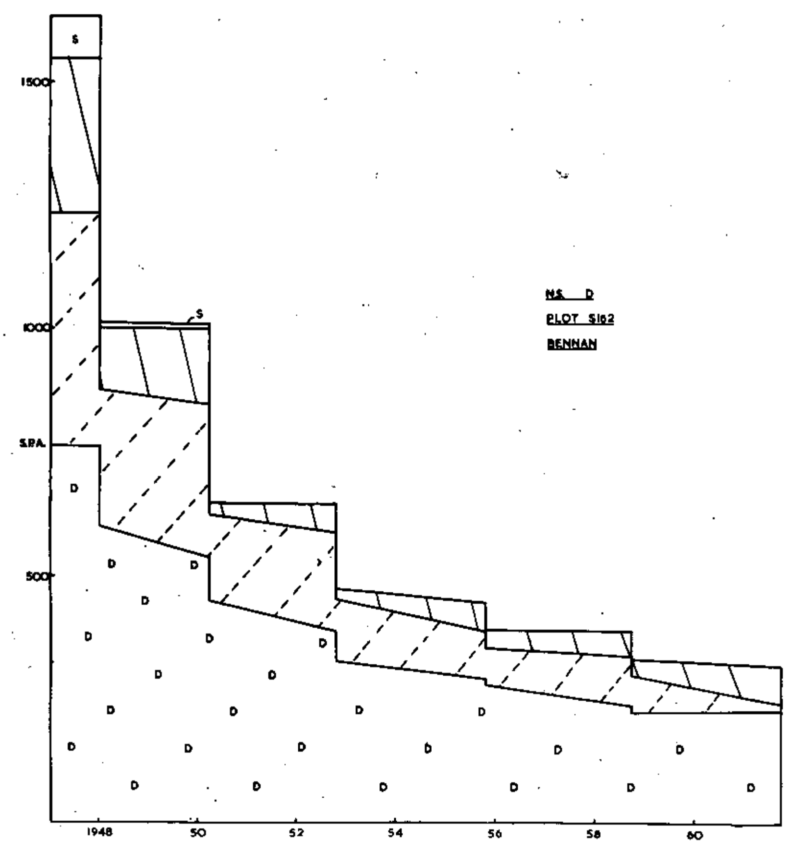

N.S. D
PLOT S162
BENNAN
1500
1000
S.P.A.
500
1948
50
52
54
56
58
60

Fig. 2

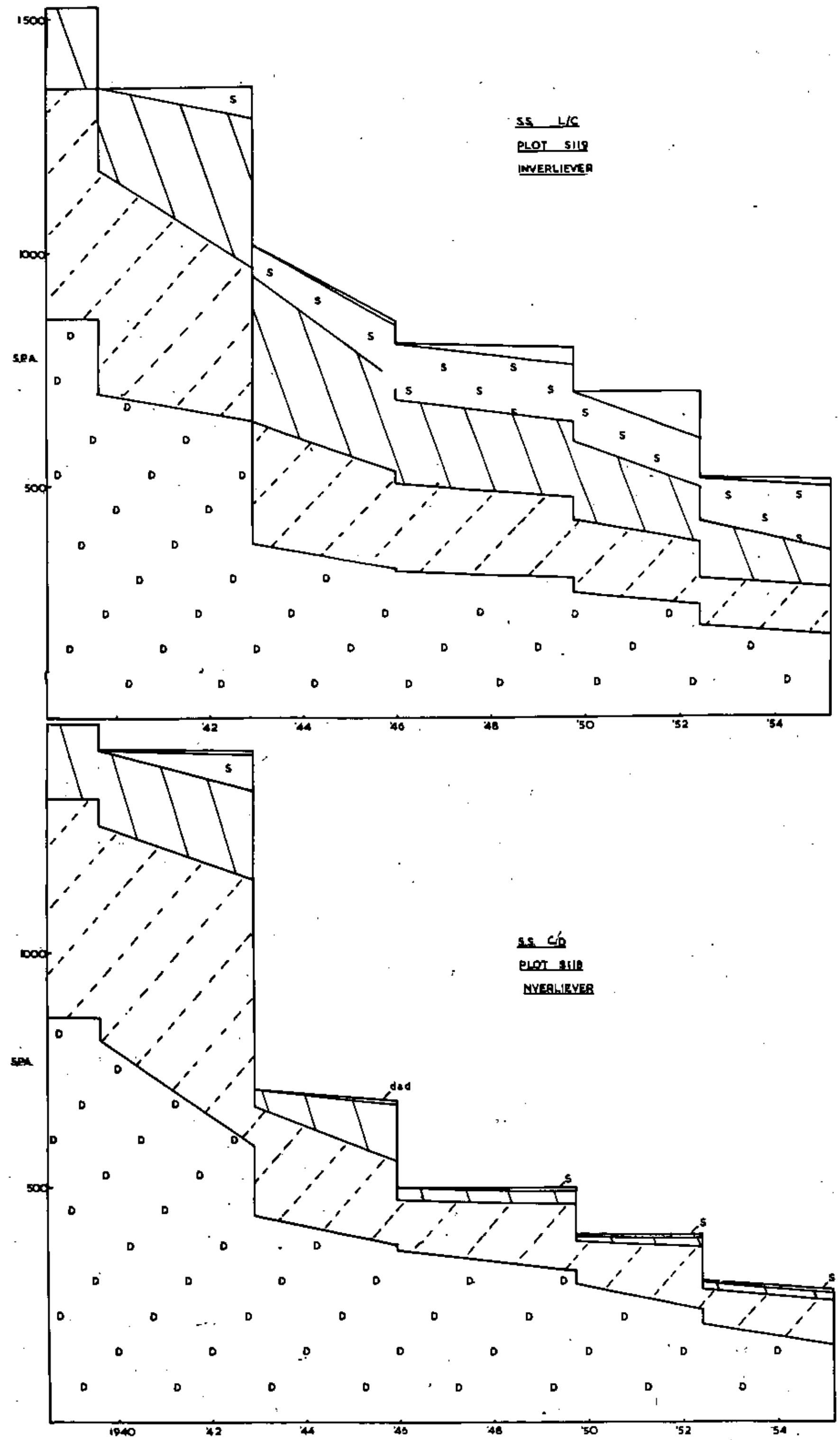
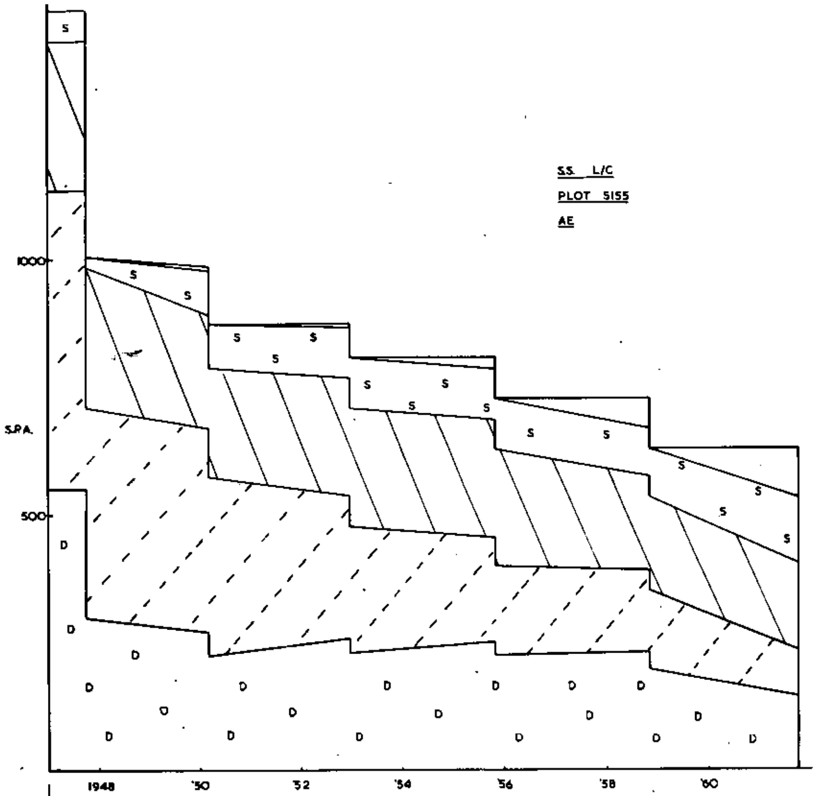
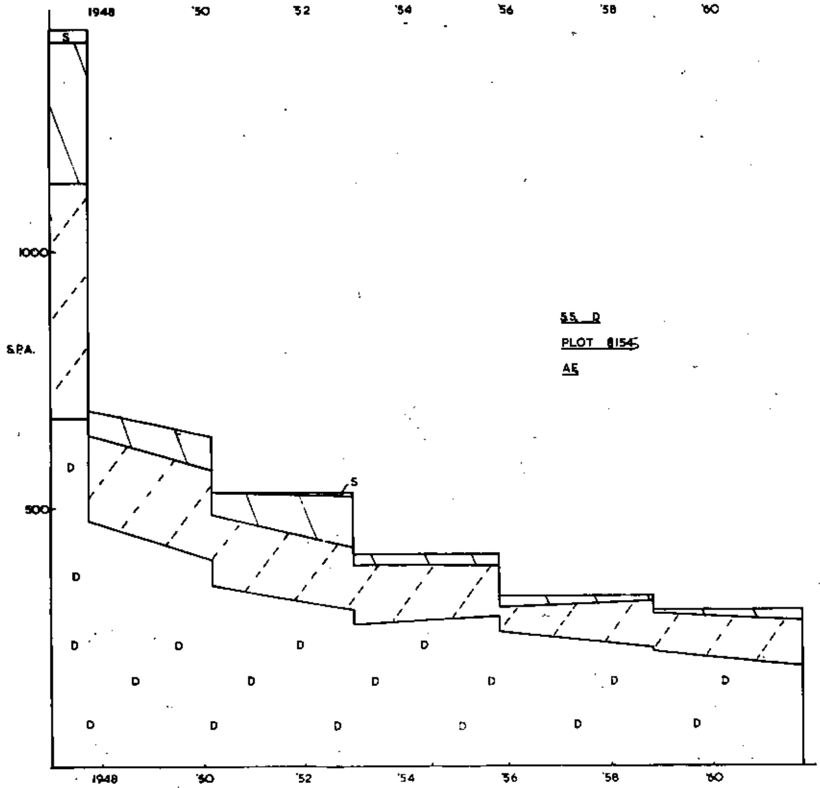

S.S. L/C
PLOT S119
INVERLIEVER
1500
1000
S.P.A.
500
'42
'44
'46
'48
'50
'52
'54
S.S. C/D
PLOT S118
NVERLIEVER
1000
S.P.A.
500
dad
1940
'42
'44
'46
'48
'50
'52
'54

Fig. 3

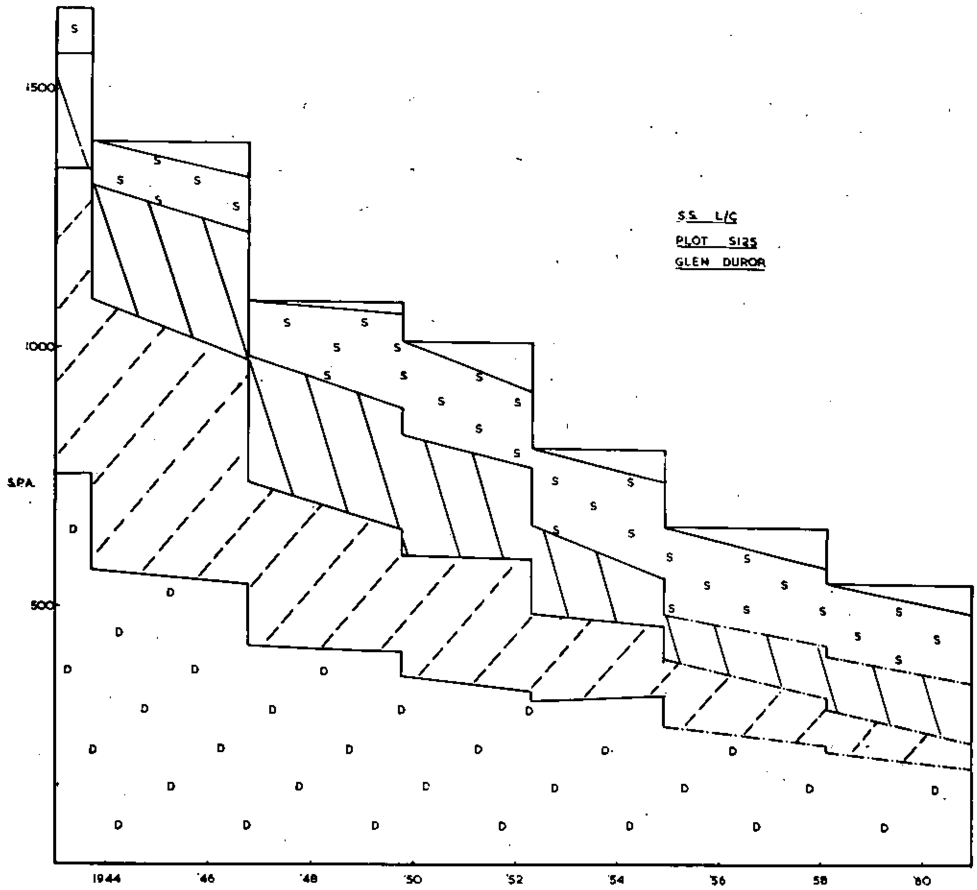


S.S. L/C
PLOT 5155
AE
1000
S.P.A.
500
1948
'50
'52
'54
'56
'58
'60



S.S. D
PLOT 6154
AE
1000
S.P.A.
500
1948
'50
'52
'54
'56
'58
'60

Fig. 4


S.S. L/C
PLOT S125
GLEN DUROR
S.P.A.
1500
1000
500
1944
'46
'48
'50
'52
'54
'56
'58
'60

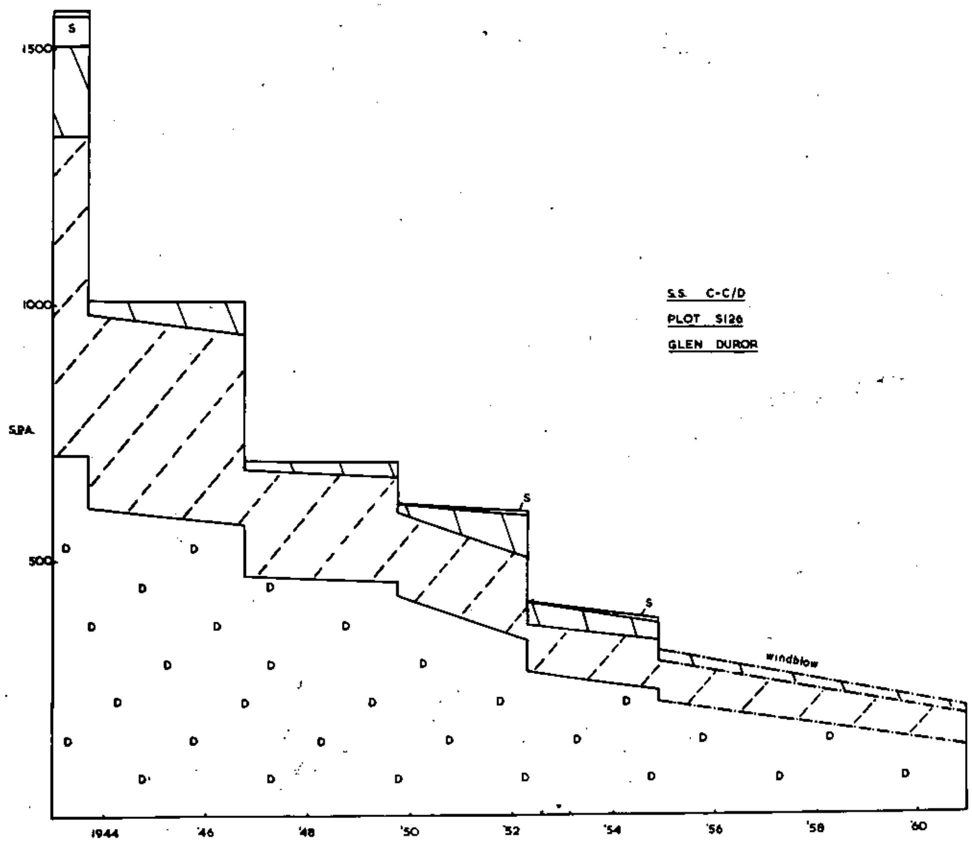

S.S. C-C/D
PLOT S126
GLEN DUROR
S.P.A.
windblow
1500
1000
500
1944
'46
'48
'50
'52
'54
'56
'58
'60

Fig. 5

Table 15. - Change of class of individual trees over 14-17yrs.

		Bennan		Ae		Inverlr.		Duror		Ae
plot		162	163	155	154	118	119	126	125	152
grade		D	L/C	D	L/C	C/D	L/C	C/D	L/C	L/C
area(acs.)		.3	.3	.175	.3	.225	.225	.321	.226	.383
period yrs/		14	14	14	14	15	15	17	17	14
initial age		22	22	20	20	16	16	20	20	20
orig. cl.	pres cl.	number of individuals per plot								
	1	68	66	32	39	36	40	39	43	68
	2	20	17	10	9	21	18	16	9	11
dom.	3	5	11	2	1	2	5	2	8	1
	4	-	-	-	-	1	5	-	1	-
	5	-	1	-	-	-	-	-	-	-
thinned		136	148	159	116	134	125	169	110	163
	1	-	-	2	2	1	-	4	-	5
	2	1	16	5	15	-	5	4	2	16
codom.	3	6	40	2	31	1	11	3	19	28
	4	-	26	-	20	-	23	-	24	8
	5	-	7	-	8	-	2	-	10	2
thinned		134	46	128	98	103	70	190	78	85
	1	-	-	-	1	-	-	-	-	-
	2	-	-	-	2	-	-	-	-	2
sub.	3	1	2	-	18	-	1	-	-	35
	4	-	31	-	18	-	3	-	6	49
	5	-	20	-	21	-	1	-	3	28
thinned		93	34	83	27	36	34	57	41	104
	1	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-
suppr.	3	-	1	-	1	-	-	-	-	-
	4	-	3	-	-	-	-	-	-	-
	5	-	4	-	-	-	-	-	-	2
thinned		26	16	7	17	0	0	18	20	67

Results

The initial impression from a perusal of Figs. 1-5 is of a majority of lines sloping from left to right, indicating the overall downward movement of trees through the classes.

Taking each class in turn and making comparisons where possible between the thinning methods, some interesting features emerge.

The dominants tend to be the most stable, in the sense that they are least liable to change their class, of the classes. Here however, there is a noticeable difference between the dominants in each pair of plots. The dominants of the L/C grade plots appear to be rather more stable than those of the low thinned plots, and where as in the latter there is generally a steady though small loss to lower classes, the former suffer few losses and occasionally a net gain between thinnings. In the upper canopy as a whole however, there is no obvious difference between treatments in net movements of trees, which in fact are almost invariably net losses. In contrast to the dominants there appears to be more stability among codominants in the C-D thinning plots than in the L/C plots.

Sub-dominants tend to accumulate in C-D thinnings, there being fewer losses to lower classes than gains from higher. In L/C plots sub-dominants tend to diminish in number with slightly greater losses than gains. The difference in numbers of sub-dominants in the L/C and C-D plots should be noted with respect to these observations.

Suppressed/

Suppressed trees are rare in the C-D plots and dead and dying trees are absent. Numbers of suppressed trees remain constant in the L/C plots, with a pronounced accumulation of dead trees within each period.

A relatively higher proportion of dominants remain after 6-7 thinnings in the low thinned plots, than in the L/C plots where the proportion of dominants is little changed from the period prior to first thinning.

Of the 42 separate periods for which trends were observed there were 7 net gains in numbers of dominants, 3 occurring in low thinned plots, 4 in L/C plots. There is only one record of a net gain to the upper canopy as a whole.

The most striking feature of Table 15 is again the over-all downward movement of trees which takes place through the canopy classes.

The majority of initially dominant trees tend to persist in both grades and there is little difference in the degree to which this is true in either method of thinning. In a few cases a dominant is seen to have moved down three classes over the 14-17 year period. The majority of original codominants are found to occupy lower classes at the end of the period, though in the low thinning plots the thinning has obscured movement somewhat. The same trend is continued in the sub-dominants in the L/C plots where the trees remaining in that class constitute a very small fraction of the originals.

Those trees which have moved up are underlined in Table 15. On the whole they constitute a very small though not entirely/

entirely insignificant fraction of the original number. Again there is no obvious difference in the two thinning methods regarding the occurrence of upward movements.

Only one tree remains which has succeeded in moving up two classes.

Regression analyses

The two methods of investigating tree movements outlined above failed to show any substantial differences in the overall movements of trees from one class to another in the two methods of thinning. Further examination of the effect of thinning on movements was thus considered desirable.

Two expressions for inter-class movements were computed for every plot for each period between thinning during which total stocking remained constant. The degree of crown thinning for the thinning carried out at the beginning of each of the periods concerned was expressed in three different ways. Regression analysis was then carried out between each of the thinning and movement expressions.

The expressions for tree class movements were:

a) the net numbers of downward movements in the plot expressed as a percentage of the total stocking. One tree moving down two classes constitutes two movements and is equal to two trees moving down one class. (m_1)

b) the net numbers of downward movemnts from the first three tree classes/

classes i.e. the dominants, codominants and sub-dominants expressed as a percentage of the total numbers of trees in these classes. (m_2)

The expressions for thinning were:

a) the ratio of the mean g.b.h. of the thinning to the mean g.b.h. of the maincrop. (the d/D ratio) (t_1)

b) the percentage number of trees of the upper canopy removed in thinnings. (t_2)

c) the expression $(t_2 \times 3p)/(2p + 100)$ where p denotes the percentage of the total stocking before thinning constituted by the dominants and codominants. (t_3)

The third index (t_3) incorporates the expression $3p/(2p + 100)$ the value of which depends on the stand structure and embodies the hypothesis that one element of the upper canopy occupies three times as much space as one element of the lower canopy.

The results of the regression analyses are shown in Table 16. Data from all plots have been pooled in the analysis, giving 37 sets of variables in all.

The simple conclusion to be drawn from the results is that the degree to which the upper canopy is opened in thinning influences the proportion of trees moving down from class to class. The analyses show that only when the effect of initial upper/lower canopy class distributions and the difference in space occupied by different elements are considered does the relationship between thinning in the upper canopy and ensuing tree class movements become significant.

Table 16.

Regression	Constant a	Coefficient b	Value of 't' 35 deg.frdm.
$t_1\hat{d}_1$	0.913	-0.0005	0.2898
$t_1\hat{d}_2$	0.904	-0.00007	0.0339
$t_2\hat{d}_1$	18.539	-0.1597	1.8422
$t_2\hat{d}_2$	18.611	-0.1847	1.7926
$t_3\hat{d}_1$	16.913	-0.1729	2.1903^{xx}
$t_3\hat{d}_2$	16.763	-0.1898	2.0083

The regression equations are of the form $t = a + bd$.
The symbol x denotes significance at the 5% level.

The d/D ratio is shown not only to be unrelated to the proportion of movements occurring following thinning, but the correlation coefficients of t_1t_3 and t_2t_3 were -0.0491 and -0.0219, showing that as an index of crown thinning it is valueless.

2. The distribution of increment between tree classes

In each plot the increment over the 14-17 year period of all those trees remaining at the end of the period was calculated. This was deduced from measurements of g.b.h. which are recorded at every assessment in F.C. sample plots. The g.b.h. figures were converted to volume figures from volume tables specially constructed for each plot. The use of basal area increment was considered ill-advised due to the differences in form factors which may result from different treatments. Volume tables were produced using the sample tree measurements which are normally made in sample plot assessments, and additional volume measurements were taken from the available records of trees removed as thinnings. It was found that no differences existed between the volume/g.b.h relationships of the sample trees and the thinnings, thus it was considered justifiable to use the latter to augment the former in preparing volume tables. In two cases only (Plots 118 and 119, at final assessment) it was found that insufficient sample trees and thinnings were available for the construction of a volume table. In such cases, a Forestry Commission tarriff table (Hummel,1956) was used, the tarriff being obtained by consulting the recorded top height of the stand at the time (Finch,1957) in conjunction with a consideration of the volumes of the available measured trees. Two volume tables were thus prepared for each plot. Problems/

Problems arise in comparing the increments of trees of different class over the 14-17 year period in that the allocation of trees to classes is based on the last assessment. This takes no account of the duration of the tree in that partisular class. Ideally, comparisons should be made between trees which have maintained their original class throughout, but the paucity of these in certain cases makes this impracticable. In Tables 17 and 18 individual classes as defined above have been further subdivided according to their original class which to some extent overcomes the problem. In many of these sub-divisions, numbers are so few as to make comparisons invalid. This is due to the method of volume increment estimation which is based on averages, and individuals can be expected to deviate significantly from the average figure.

The results are presented in tabular form. Table 17 shows the absolute increment (average) per tree over the whole of the period concerned, in each of the tree classes. In Table 18, the increments in each class are expressed as a percentage of the volumes of the classes at the beginning of the relevant period, considering only the individuals remaining at the end of the period. Table 19 shows the increment percents of the different classes expressed as a percentage of the increment percentages of the dominants. In all cases each plot is considered separately and the data are arranged for ease of comparison.

Table 17. - Absolute average increments of trees of different class

pres. cl.	orig. cl.	Bennan L/C 163	Bennan D 162	Ae L/C 154	Ae D 155	Inverln. L/C 119	Inverln. C/D 118	Duror L/C 125	Duror C/D 126	Ae L/C 152
doms.	1	10.0	12.5	13.0	9.9	14.4	19.5	19.2	21.1	15.9
	2	-	-	$\underline{11.9}$	$\underline{7.5}$	-	$\underline{10.4}$	-	$\underline{16.4}$	$\underline{8.9}$
	3	-	-	$\underline{6.7}$	-	-	-	-	-	-
wtd.aver.		(10.0)	(12.5)	(12.8)	(9.8)	(14.4)	(19.3)	(19.2)	(20.6)	(15.4)
codoms.	1	4.6	6.0	7.1	6.4	13.1	11.6	9.2	9.6	7.4
	2	3.4	$\underline{4.1}$	5.0	$\underline{6.4}$	$\underline{7.7}$	-	$\underline{5.7}$	$\underline{9.9}$	5.9
	3	-	-	$\underline{3.9}$	-	-	-	5.5	-	$\underline{5.5}$
wtd.aver.		(4.0)	(5.9)	(5.6)	(6.4)	(11.9)	(11.6)	(8.6)	(9.7)	(6.5)
subs.	1	2.4	$\underline{2.5}$	$\underline{.9}$	$\underline{4.2}$	$\underline{4.1}$	$\underline{8.7}$	5.7	9.0	3.7
	2	1.7	2.6	3.0	$\underline{3.3}$	2.9	$\underline{6.2}$	5.6	$\underline{4.8}$	2.5
	3	$\underline{.7}$	$\underline{2.6}$	1.5	-	$\underline{1.3}$	-	-	-	1.8
	4	$\underline{1.4}$	-	$\underline{4.3}$	-	-	-	-	-	-
wtd.aver		(1.8)	(2.5)	(2.4)	($\underline{3.8}$)	(3.1)	($\underline{7.9}$)	(5.6)	($\underline{6.5}$)	(2.4
suppr.	1	-	-	-	-	$\underline{2.9}$	$\underline{3.5}$	$\underline{.7}$	-	-
	2	1.5	-	1.6	-	1.8	-	1.7	.7	1.3
	3	.4	-	.7	-	$\underline{1.6}$	-	.5	-	.8
	4	$\underline{.1}$	-	-	-	-	-	-	-	-
wtd.aver		(0.54)	-	(1.18)	-	(1.9)	$\underline{(3.5)}$	(.6)	-	(.9)
dead & dying	1	$\underline{.44}$	-	-	-	-	-	-	-	-
	2	.3	-	.77	-	$\underline{1.69}$	-	.46	-	.6
	3	.08	-	.54	-	$\underline{2.4}$	-	$\underline{.19}$	-	.46
	4	$\underline{.07}$	-	-	-	-	-	-	-	.02
wtd.aver.		(.14)	-	(.60)	-	$\underline{(1.94)}$	-	(.37)	-	(.45)
period		14 yrs.		14 yrs.		15 yrs.		17 yrs.		14 yrs.

N.B. Underlined figures are based on fewer than 6 trees

Table 18. - Increment % of individual trees

pres. cl.	orig. cl.	Bennan L/C 163	Bennan D 162	Ae L/C 154	Ae D 155	Inverlr. L/C 119	Inverlr. C/D 118	Duror L/C 125	Duror C/D 126	Ae L/C 152
doms.	1	499	633	538	471	511	750	488	473	723
	2	-	-	1761	604	-	633	-	312	712
	3	-	-	1240	-	-	-	-	-	-
wtd.aver.		(499)	(633)	(552)	(476)	(511)	(748)	(488)	(456)	(723)
codoms.	1	426	466	463	371	545	623	316	382	524
	2	339	725	485	516	707	-	440	448	623
	3	-	-	473	-	-	-	-	-	618
wtd.aver.		(385)	(471)	(475)	(409)	(563)	(623)	(317)	(394)	(570)
subs.	1	251	209	134	250	263	603	307	369	319
	2	229	295	292	394	251	487	182	278	355
	3	200	461	362	-	985	-	-	-	402
	4	165	-	993	-	-	-	-	-	-
wtd.aver.		(233)	(260)	(310)	(298)	(255)	(568)	(226)	(322)	(375)
suppr.	1	-	-	-	-	176	302	28	-	-
	2	93	-	180	-	217	-	60	-	177
	3	103	-	169	-	334	-	73		166
	4	10	-	-	-	-	-	-	-	-
wtd.aver.		(94)	-	(177)	-	(212)	(302)	(59)	-	(169)
dead	1	122	-	-	-	-	-	-	-	-
	2	43	-	88	-	204	-	43	-	112
	3	31	-	128	-	285	-	126	-	127
	4	23	-	-	-	-	-	-	-	67
wtd. aver.		(38)		(111)		(231)		(47)		(125)
period		14 yrs.		14 yrs.		15 yrs.		17 yrs		14yrs.

N.B. Underlined figures are bases on fewer than 6 trees.

Table 19. - Weighted average increment percentages (Table 18) in relation to those of the dominants

class	Bennan 163 L/C	Bennan 162 D	Ae 154 L/C	Ae 155 D	Inverlr. 119 L/C	Inverlr. 118 C/D	Duror 125 L/C	Duror 126 C/D	Ae 152 L/C
dominants	100	100	100	100	100	100	100	100	100
codominants	77	71	86	86	110	83	65	86	79
sub-dominants	47	39	56	<u>62</u>	49	<u>76</u>	46	70	52
suppressed	19	-	32	-	41	<u>40</u>	12	-	23
dead & dying	8	-	20	-	<u>45</u>	-	10	-	17

N.B. Underlined figures are based on fewer than 6 trees.

Results

Table 17 indicates clearly the contribution to increment of the different classes. Indeed, not infrequently the increment contribution of an average dominant is greater than the sum of the increments of average trees in the remaining classes. Within each class, the greater absolute increment in general is shown by those trees of higher class origin. Trees of the low thinning plots tend to have greater absolute increments than those of the L/C plots.

It has not been possible to relate increment to growing space since crown measurements are not available. The best measure of efficiency has therefore been considered to be increment percent, which is given in Table 18. The superiority of the dominants is clearly demonstrated here also. No clear pattern is found regarding the effect of the original class within each class on increment percentage.

To show more clearly the differences between treatments the increment percentages have been expressed in relation to that of the dominants in each plot. (Table 19) The sub-dominants are shown to be no more efficient in the crown thinning than in the low. Similarly no distinct differences are apparent among the co-dominants of each treatment.

3. Discussion

It is unfortunate that sample plot data was not available for selection thinning, or even the Scottish Eclectic thinning, where thinning in the upper canopy is heavier than in either the C-D or L/C thinning grades. Whilst there are substantial differences in the L/C and C-D thinning methods, the results of this study tend to suggest that over a period of 15 years or so there is no great difference between the two in terms of thinning in the upper canopy. This feature is illustrated in Fig. 6. The heavier thinning among dominants in the L/C grade plots presumably accounts for the greater stability of this class in these plots. Though the total numbers of trees in the upper canopy removed in thinning appears to be greater in the low thinnings than in the L/C plots, the crown thinning effect, considering the space occupied by each element, is probably similar in both methods of thinning. The terms low and crown thinning are therefore considered to be misleading when applied to these methods.

On this evidence it is perhaps not surprising that there are no substantial differences in overall movements of trees in the two thinnings. Regression analyses have shown however, that the degree to which the upper canopy is opened affects the proportion of downward movements of trees between canopy classes. On the basis of the range of crown thinnings applied here, and this point must be stressed, the suggestion is that downward movements can not be halted, short of removing the upper canopy entirely.

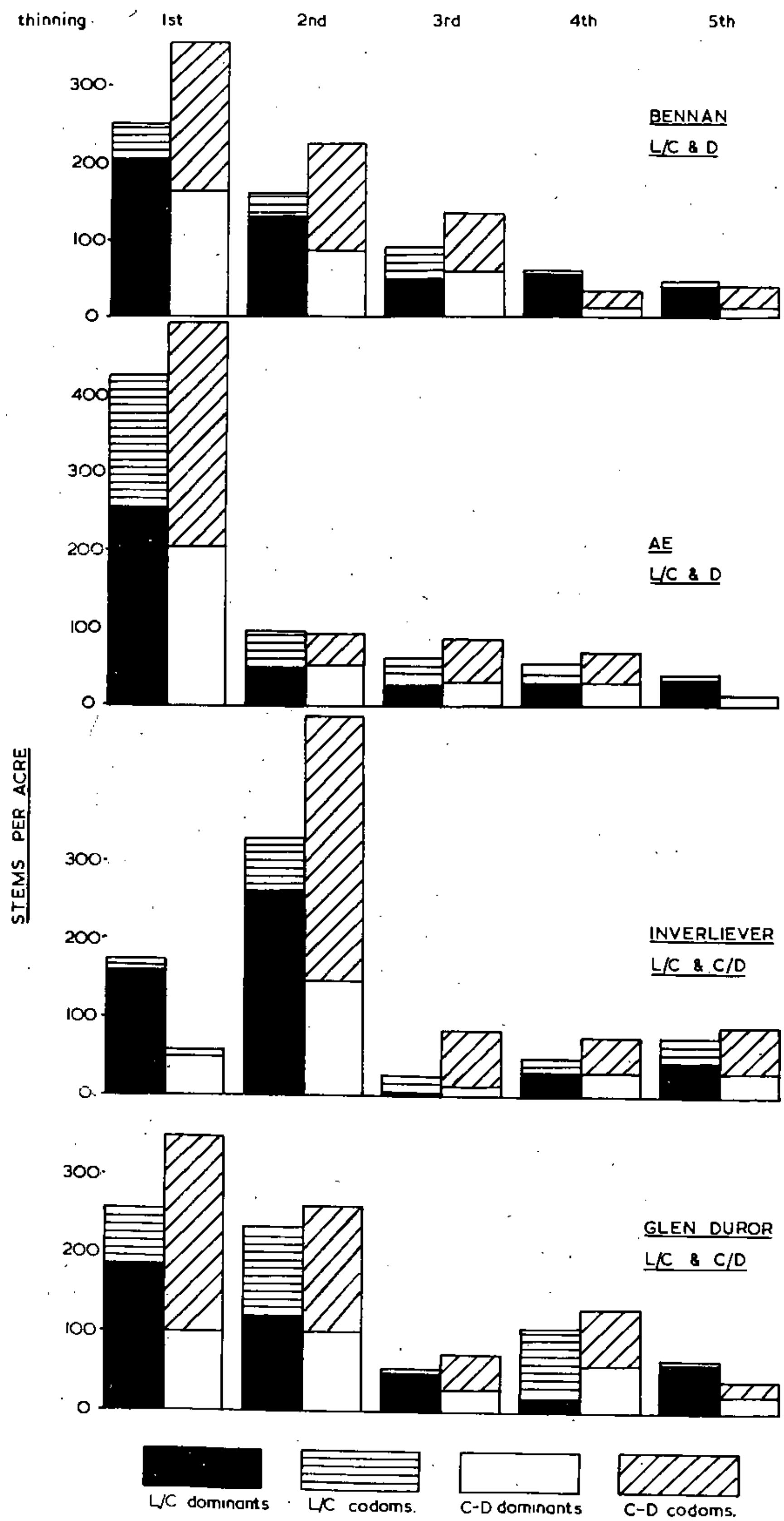

thinning
1st
2nd
3rd
4th
5th
STEMS PER ACRE
0
100
200
300
400
BENNAN
L/C & D
AE
L/C & D
INVERLIEVER
L/C & C/D
GLEN DUROR
L/C & C/D
L/C dominants
L/C codoms.
C-D dominants
C-D codoms.

Fig. 6

The occurrence of upward movements is ~~are~~ much too rare to be considered to have any practical value.

In general the results of this study are similar to the conclusions reached in Chapter 5 from reviewing the literature on the subject in respect of the overall downward movements, and rare upward movements of trees. No evidence is found to support the exceptional views of Abell and Kantor, that dominance is not permanent.

The investigation of Hummel and Guillebaud was conducted in the same manner as that described above. Though their findings are similar to those described above , they record rather more upward movements of trees, though the numbers of these are very small nonetheless. A notable point in Nyssonnen's investigation was the fact that thinning did not alter the number of upward movements occurring in Scots pine plots. Warrack found no differences in the incidence of upward movements in plots of Douglas fir under three different treatments. In the light of these findings and the reults of the present study, it would seem that upward movements are not influenced by treatment, but that, as suggested by Meyer (1965), such movements may be governed largely by genotype.

The subject of the effect of the degree of canopy opening on the proportion of trees moving down through the classes is absent from the literature.

It would have been desirable to express increment in terms of crown projection. However, in the absence of this, increment percentage is a useful substitute.

The/

The greater absolute increment of the upper canopy elements in the C-D plots suggest that the retention of a lower canopy has a depressing effect on the increment of the dominants and codominants, contrary to the opinions held by some (e.g. Macdonald, 1963) that the removal of stems of the lower canopy has no effect on the development of the trees of the upper canopy.

No differences in the relative efficiencies of the sub-dominants are apparent between the two methods of thinning, presumably reflecting the similar degrees of thinning in the upper canopy. Kramer (1965) concluded after comparing the efficiencies of the sub-dominants in the B and L/C grades of the Bowmont plots, that the sub-dominants were more efficient by a factor of 8 in the L/C plots. He failed to point out that this increase was true also of the sub-dominants in the C grade plots.

In general, the results of this study of increment distribution agree with the conclusions reached in Chapter 2, on the evidence of the literature.

The table of mean annual increments produced below shows little difference in the two methods of thinning. This is not unexpected at this stage if the results of the Bowmont plots assessments are any guide.(MacKenzie,1962)

Table 20 - Mean annual increments of F.C. sample plots.

plot	125	126	163	162	155	154	118	119	152
M.A.I.	234	240	160	154	152	164	267	240	198 H.ff.
age	36	36	36	36	34	34	31	31	34
grade	L/C	C/D	L/C	D	D	L/C	C/D	L/C	L/C
	Duror		Benmore		Ae		Inverliever		Ae

Summary

The conclusions arising from the investigation, under the conditions of age, species etc. previously stated are enumerated below.

1. There is a considerable net downward movement of trees through the canopy classes during the development of the stand. This is true of both the C-D plots and the L/C plots.

2. Dominant trees are most stable, and are rather more so in L/C plots.

3. There is no difference in the stability of the upper canopy generally in the two thinning grades.

4. Tree movements through the classes culminate in the accumulation of trees in the sub-dominant and dead and dying classes in the C-D and L/C plots respectively.

5. Different thinning methods result in a higher proportion of dominants in the final crop of the C-D plots than initially, but this is not so in the L/C plots.

6. Net gains occurred in the dominant classes in 7 out of 42 thinning intervals, but the numbers of trees which were found to have moved up one class after 14-17 years was a very small fraction. Upward movements are therefore considered rare, and appear to be independent of treatment.

7. An ever increasing proportion of the original trees was found in lower canopy classes, with increasing dominance. This suggests that the downward movement accelerates with lower positions in the canopy.

8. Regression analyses showed the degree to which the upper canopy is opened affects the overall downward movement of trees. The greater the canopy opening, the smaller is the proportion of trees moving downwards.

9. Greater absolute increment and greater efficiency is associated with greater dominance.

10. Absolute increment is greater in the upper stand elements of C-D thinning plots than in L/C plots.

11. There is no evidence of differences in efficiency of sub-dominants in the two methods of thinning.

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Chapter 8.

A Study of the Increment of Individual Trees under Different Thinning Treatments over One Growing Season

Object The object of the experiment described here was to establish the extent to which increment is dependent on the dominance, i.e. height and g.b.h., of the individual tree, certain crown parameters, and the effect of thinning on the relations between these variables, when conducted principally in the upper canopy.

Location The experiment is located in Drumtochty Forest in Kincardineshire, which is part of the forest estate of the East Scotland Conservancy of the Forestry Commission. The forest lies on the south face of the Grampians, and borders the low-lying Howe of the Mearns. Compartment 62 in which the experiment is located, lies on the south side of Drumtochty Glen, south of the Highland Boundary Fault, at an elevation of approximately 500 feet. The geology of this region is Lower Old Red Sandstone.

The annual rainfall is about 35 inches, of which 15-20 fall during the growing season. The mean monthly minimum and maximum temperatures are about 37°F. and 53°F respectively. The area is in the B1b sub-region of Anderson and Fairbairn's climatic divisions of Scotland (1955) which specifies among other features, a growing season of 175 days for the locality.

<u>The experimental site</u> The experiment covers an area of about one acre in compartment 62 on a concave slope facing east of north and averaging 15^{o}.

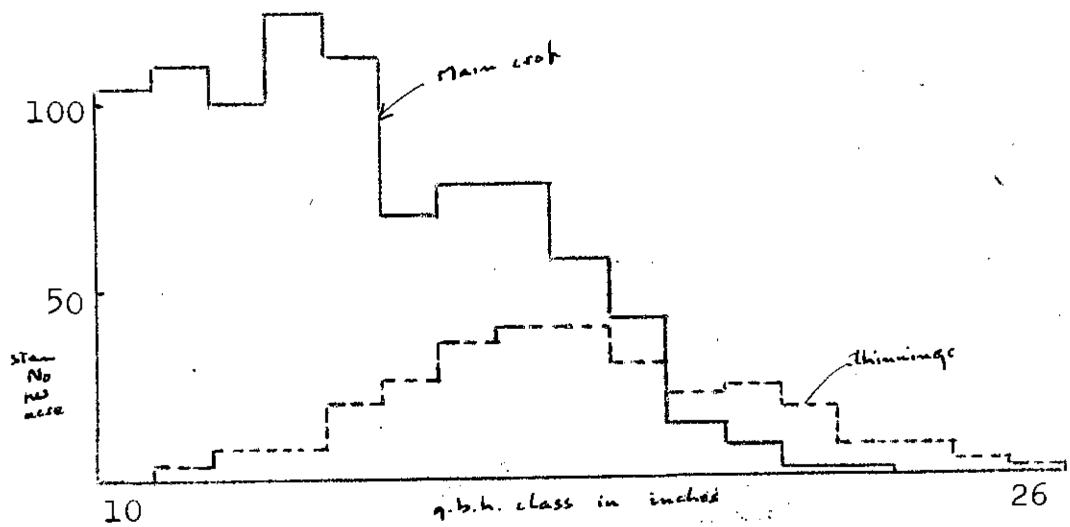
There is evidence of former tree cover on the site, and it seems likely that this area was part of the forest estate of the previous owner (Anon, 1953). Remnants of <u>Calluna vulgaris</u> suggest that this was the dominant vegetation before planting of the present stand.

The <u>soil</u> is a podzol derived from Old Red sandstone. Occasionally there is evidence of buried humus horizons where for unknown reasons the soil has been disturbed. It is an extremely free draining soil, and surface run-off was never observed during the period since the experiment was established. Nor was any water observed in drains.

The present <u>stand</u> is Sitka spruce, planted in 1942 at a spacing of rather less than 5 x 5 feet. The current height growth is greater than might be expected in a Quality Class V. stand, this Q.C. being based on the top height of the stand. The soil ~~type~~ also may be expected to support a higher yielding crop, but there is no evidence of early check which may have justified the seemingly low quality class.

Half an acre of the stand was demarcated in 1964. It was subsequently marked for thinning and thinned in April of that year. The <u>thinning</u> was an experimental one than being/

being tried out by the Conservator of Forests, East Conservancy, (Mr.F.Oliver) and was intended for demonstration purposes. The surrounding area was not thinned. No previous thinning had been done in the compartment. The thinning method used may be described as a selection thinning. Emphasis was placed on removing stems of merchantable proportions. This in fact meant the removal of trees mostly from the dominant and co-dominant classes.



The above diagram shows the distribution in girth classes at one inch intervals, from 10 inches to 26 inches g.b.h., of the maincrop after thinning and the thinnings. The former are shown by the continuous lines, the latter by the broken lines. (Stems/acre.)

The top height of the stand at the time of thinning was 32 feet. 335 stems per acre were unmeasurable, i.e. less than 10" g.b.h. The tarrif number was given as 18. Other features of the thinning and maincrop are given/

given below.

	maincrop	thinnings
Stems/acre.	902	298
Basal area/ac.	80	42 sq.ft.(Hoppus)
Volume	983	625 H.ft.
Vol/tree (measurable stems)	1.09	2.1 H.ft.

It is clear from these figures and from the diagram that the thinning method is an extremely heavy crown thinning.

Methods

Before the start of the 1965 growing season, 60 trees were selected. 30 of these were selected in the thinned area. It was decided that the trees selected in this area must have been released by the removal of at least two adjacent trees which caused breaks in the canopy immediately contiguous to the crown of the selected tree. Trees meeting this requirement were then selected at random in the plot. After having selected the greater part of the required number, the remainder were selected so that an even range of girth classes were obtained, excluding trees less than 8½" g.b.h. Similar methods were employed in sampling the area surrounding the plot, except that the released condition was substituted by one which required that trees selected must not be adjacent to gaps in the canopy, the occurrence of which were/

were in any case infrequent. 30 trees were thus selected as control trees.

Dendrometer girth bands were used to measure girth increment of the selected trees. The bands (illustrated) were constructed by the method of Liming (1956) with minor modifications. They were constructed from aluminium tape, 0.5 inches wide by 0.015 inches thick. This was coated with black stoving enamel paint, and heated in an oven at 300°C for approximately half an hour. This coating reduces corrosion, makes the bands less visible to the public, and most important, makes scale readings considerably easier. Two scales were marked on the tape, one in inches and tenths, the other, the vernier scale, consisting of ten divisions of .09 inches. The vernier scale was applied in the field to ensure correct alignment of the two scales. The arrangement of the two scales is shown in the photograph. Changes in girth of 0.01 inch are recorded by the bands. Stainless steel springs which provide sufficient tension to hold the scales in the correct position were constructed by spinning 26 gauge stainless steel wire under constant tension on a revolving spindle.

Minimal preparation was required of the bark surface before installing the bands since at this age Sitka spruce bark does not tend to flake. Removal of needle scales, however, was required where bands were installed within the crowns of trees. Care was taken to ensure that resin/

Two versions of the dendrometer girth band are illustrated here. The upper one is that described by Liming (1957) and is the type which was used in this investigation. The lower one is a modification of the same principle, recently described by Larsson and Jaciw. They are mounted on a specimen of Scots pine, a species which requires rather more bark preparation than does Sitka spruce at the time of first thinning.

resin sacs and other irregularities in the bark were avoided ensuring maximum area of contact between band and tree. Two tacks were placed under the lower rim of the band at opposite points to ensure that the band remained in the same position. The effect of temperature on the bands was ignored. Aluminium has a coefficient of linear expansion of 0.23×10^{-4}, so that for a band 18" in circumference to alter 1/100th of an inch would require a temperature change of $24^{\circ}C$ which far exceeds the range encountered in the shade in the period during which readings were taken. Sunflecks were not a problem. Over the whole growing season the bands were found to function perfectly. Similar bands have been found to function satisfactorily up to periods of five years, (Larsson, Jaciw, and Roos, 1964).

One band was installed at breast height on every selected tree. Every fourth tree, in each area, in decreasing order of g.b.h., starting with the largest, had a second band installed at mid-height. In the smallest trees where the mid-height girth was less than 8 inches, it was found impracticable to instal bands at that point. Thus seven trees in the thinned area and six in the control area have bands at mid-height. The girth at the relevant points was measured before the bands were placed in position.

Installation of the bands at breast height was completed by 11th April and the upper bands by 25th April during which/

which period no growth was recorded. The scales were subsequently read at fortnightly intervals throughout the growing season.

The height of each selected tree was measured using a Blume-Leiss altimeter. In the control area this was achieved with some difficulty, owing to the problem of sighting leading shoots. Heights were measured in July and were taken to the point of the previous season's leader.

A graduated stick was used to measure the height of the lowest live whorl i.e. where more than half the branches of the whorl were bearing green needles. Subtracting this from tree height gave the measure of crown depth of each selected tree.

Crown projection was measured with an instrument specially designed for the purpose. Its use permits the vertical projection of any point of the crown to be located on the ground or wherever desired.

The instrument, illustrated here, incorporates a gimbal within which is mounted a brass rod some 3 feet long, supporting a mirror and sighting device, all of which are freely suspended so that the whole lies in a vertical position regardless of the position of the user. The operator positions the instrument so that the crown extremity and the two points of the sighting device are aligned in the mirror. In this position the brass rod defines the vertical line below the crown point.

The crowns of spruce of this stage of development are/

The instrument used for locating
crown projection.

are not easily demarcated. Outlines tend to be highly irregular. On any crown radius, the edge of the crown was taken to be point of the third most extreme branch i.e. that point where the crown became only two branches 'deep'. Radii were measured along 6 arms, 60^{o} apart two of which lay along the magnetic N-S axis approximately. Each extremity was marked on the ground and measured later. The instrument was found to operate satisfactorily.

Measurements of crown, girth, and distance were taken for all trees less than 10 feet from a selected tree. Because of the difficulty of measurement in the unthinned area, and the time required, heights of the competing trees were not measured. Crown radii were measured at three points, two at right angles to the line joining the selected tree and the competing tree, the third along the joining line. The positions of each tree was noted on a rough sketch, so that overlapping crowns could be recorded.

From each selected tree tree counts were made using wedge prism angle guages. Two prisms were used, one of factor 20 (true measure) and one of 25. This was done to achieve another measure of tree competition.

Results

(a) The relationships between some tree variables

The following tables show the results of regression and correlation analyses conducted on the variables indicated for all selected trees in the experiment. Measurements used were those taken at the start of the growing season.

Table 21.- Correlation coefficients

	height	girth b.h.	crown proj.	crown depth	crown vol.
height	1.000				
girth	0.6337	1.000			
cr.prj.	0.5638	0.8753	1.0000		
cr.dpth.	0.9181	0.7050	0.6403	1.0000	
cr.vol.	0.6903	0.8686	0.9712	0.7697	1.000

....

Table 22. - Regression analyses

regression	coefficient	constant	value of t 58 deg.fdm.
ht./girth	0.744	20.90	6.2391
ht./proj.	0.168	28.14	5.198
ht./depth	0.857	16.86	17.639
ht./vol.	0.023	28.47	7.265
girth/proj.	0.223	9.82	13.7846
girth/depth	0.561	5.23	7.507
girth/vol.	0.025	11.23	13.351
proj./depth	2.002	-11.30	6.348
proj./vol.	0.110	6.67	31.063

N.B. All values of 't' are significant at the 0.1% level.

Crown projection was estimated as πr^2, r being the average of 6 crown radii measured for the selected tree. Crown volume was computed from the formula $\pi hr^2/3$ where h is the crown depth.

Tables 21 and 22 show the very close association between the variables. Particularly noticeable are the high degrees of correlation between tree height and crown depth and between crown projection and girth at breast height.

(b) Seasonal growth

The dendrometer bands were read throughout the growing season at approximately fortnightly intervals, except the upper bands which were read only occasionally during the season.

Figures 7 and 8 show the length of time from the date when growth was first recorded to that when last recorded, for each tree in the thinned and control areas respectively. Clearly, more frequent readings taken at the beginning and of the growing season would have established more precisely the dates of initiation and cessation of growth. None-theless there is an indication of the relation between these features and the g.b.h. of the selected tree. Initiation and cessation of growth appears earlier in trees of larger and smaller g.b.h. respectively. However, since the bands do not record less than 1/100th of an inch increase/

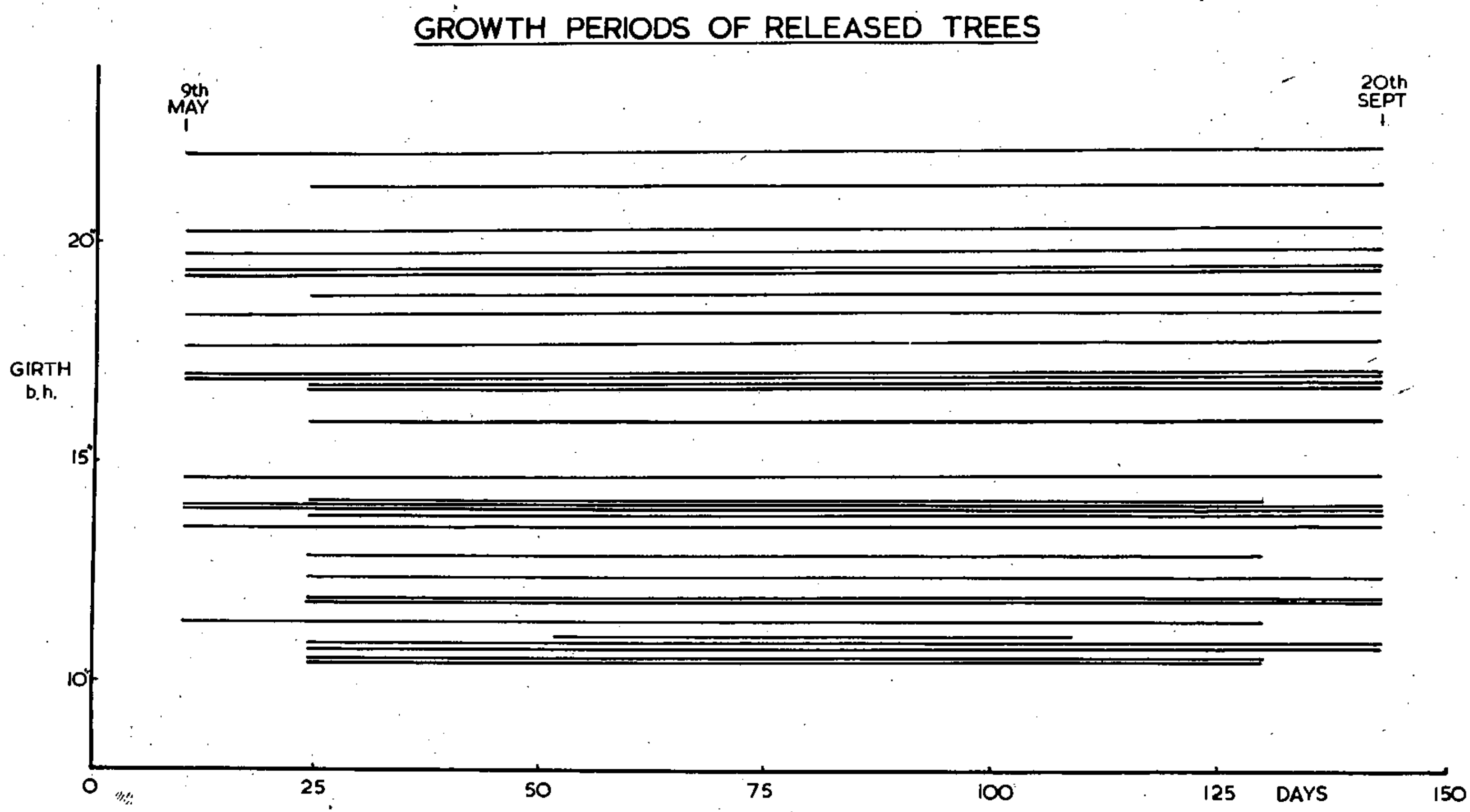

GROWTH PERIODS OF RELEASED TREES
9th
MAY
20th
SEPT
GIRTH
b.h.
20"
15"
10"
0
25
50
75
100
125
DAYS
150

Fig. 7

GROWTH PERIODS OF TREES NOT RELEASED

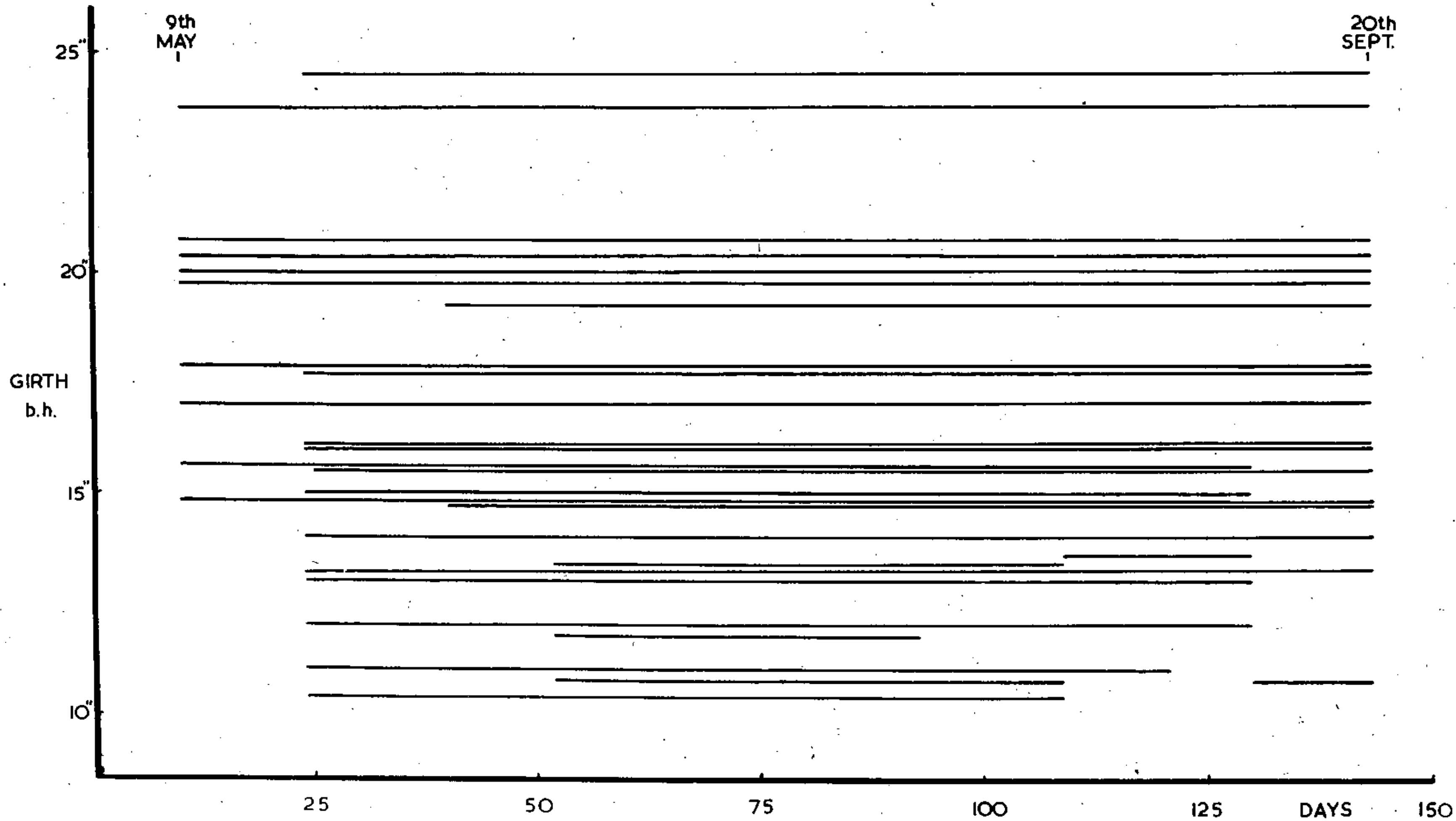


Fig. 8

increase in circumference, the possibility that growth in small trees has occasionally been undetected renders the accuracy of Figs. 7 and 8 uncertain.

Slight differences between treatments appear to exist between thinned and control trees. On the 23rd May, growth had been recorded in 29 trees in the thinned area as opposed to 21 in the control area. Similarly growth was recorded after 6the September in 24 and 18 trees in the thinned and control areas respectively.

Figure 9 shows the seasonal pattern of growth of the selected trees. Average increments of four g.b.h. categories have been shown. The categories are described below.

Table 23. - G.b.h. categories.

category	No. of trees	range of g.b.h	average girth thinned	average girth control
1..	7	over 18.5"	20.09"	21.20"
2.	7	15 - 18.5"	16.99"	16.84"
3.	8	12 - 15"	13.65"	13.97"
4.	8	less th.12"	11.09"	10.73

Growth, which was first recorded before the current year's shoots had flushed, appears to reach a maximum within 2-3 weeks of the time of being first recorded, then slows down towards the end of July.

The effect of g.b.h. and thinning on absolute girth increment need little comment here, other than to mention the fact that the effect of thinning is greatest in the third/

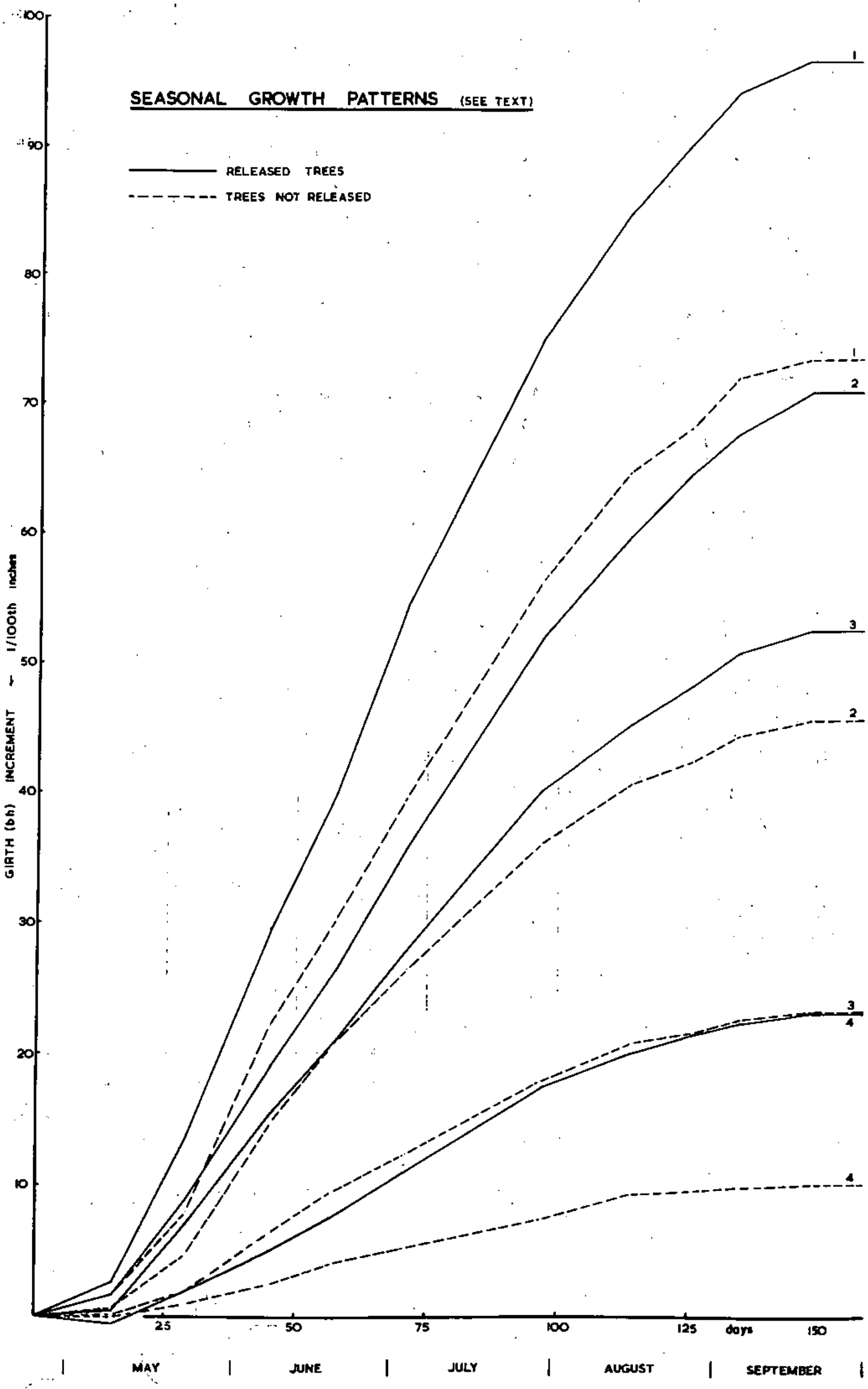

SEASONAL GROWTH PATTERNS (SEE TEXT)
RELEASED TREES
TREES NOT RELEASED
GIRTH (bh) INCREMENT ~ 1/100th inches
100
90
80
70
60
50
40
30
20
10
25
50
75
100
125
days
150
MAY
JUNE
JULY
AUGUST
SEPTEMBER
1
2
3
4

Fig. 9

third g.b.h. category which has a greater increment than the second category of control trees. Two minor features for which there is no obvious explanation, are the curious dips in the rate of increment occurring in the control trees around the end of August, and the negative increment shown by the fourth category of the released trees.

With regard to the patterns of growth recorded in the upper bands, readings taken on 9th May showed that in a few trees growth was recorded in the upper band when none was evident at breast height. Where both bands had recorded growth, this was invariably greater in the upper band. The suggestion is therefore that growth is initiated at higher levels in the tree. Comparative figures of increment recorded in upper and lower bands at 9th September are tabulated below.

Table 24. - Increments in girth to 9th Sept. (1/100")

Tree No. (thinned)	3	7	10	12	14	20	24
Abs.inc. mid-ht.	75	163	123	71	40	47	110
" " at b.h.	66	97	87	42	20	33	66

Tree No. (control)	43	44	51	58	63	69
Abs.inc. mid-ht.	54	114	72	113	38	52
" " at b.h.	27	66	34	83	23	30

....

(c) Increment

Stem volume increment and basal area increment were computed for each selected tree.

Basal area increment was calculated simply as the increase in sectional area at breast height over the growing season and expressed in square inches.

The volumes of each of the selected trees fitted with a second girth band at mid-height were calculated for the beginning and end of the growing season. Height increments were not measured but, on the basis of height-age curves for Q.C. V Sitka spruce, a height increment of 5% was assumed. Thus, using girth measurements at breast height and mid-height, and tree height, and assuming the topmost section to be conical, volumes were calculated. From these, the form factors at each period were produced and changes in these over the growing season observed.

Table 25 - Form factor changes.

Tree No.	Initial vol.	Vol. incre.	Init. form fcr.	Final f.f	Change
3	3.345	0.374	0.513	0.505	-0.0083
7	4.200	0.637	0.476	0.479	0.0029
10	3.863	0.565	0.478	0.478	-0.0001
12	1.396	0.144	0.537	0.532	-0.0053
14	0.932	0.119	0.502	0.485	-0.0173
20	1.243	0.104	0.503	0.494	-0.0095
24	2.499	0.348	0.475	0.476	0.0018
43	2.566	0.188	0.550	0.534	-0.0062
44	5.780	0.592	0.484	0.483	-0.0010
51	2.794	0.237	0.486	0.484	-0.0026
58	3.509	0.688	0.441	0.463	0.0222
63	1.401	0.089	0.602	0.589	-0.0130
69	2.062	0.155	0.476	0.469	-0.0078

The changes in form factors are given in Table 25. Trees numbered 3-24 are 'released' trees, the remainder being control trees. It can be seen that the changes in form are insignificant, and that no difference can be detected between treatments.

At the end of the growing season one or two girth measurements were taken at points other than at breast height on each selected tree, the number depending on the size of tree. Again assuming a height increment of 5%, the volumes at the end of the growing season, and hence the form factor at that time was calculated. Using the same form factor as was found at the end of the growing season for each tree, the volumes at the beginning of the growing season were calculated as form factor times height times basal area. Thus volume increment was computed as the difference between the two calculated volumes.

In all cases, volumes were calculated in true cubic feet measurement and were taken to the tip of the stem.

Linear regression

Single regression analyses were conducted between increment and g.b.h., height, crown volume, crown projection, and crown surface area of the selected trees. The thinned and control trees were treated separately. Crown volume was calculated as d x p/3 where d is the crown depth and p the crown projection. Crown surface area was taken as the lateral area of the crown (a cone) and/

and was calculated from the formula πrd where r is the crown radius. d - depth

The regressions are given in Table 26.

Table 26 - The relation between increment and tree variables

Regression		coefficient	constant	value of 't' with 28 d.f.
thinned area.				
vol.inc./g.b.h		0.0515	-0.4604	9.394
"	/height	0.0326	-0.7700	6.356
"	/cr.proj.	0.0126	-0.0019	7.283
"	/cr.vol.	0.0015	0.0604	9.741
"	/cr.sf.a.	0.0024	0.0929	12.803
b.a.inc./g.b.h.		0.2586	-2.3105	8.630
"	/height	0.1547	-3.5729	5.357
"	/cr.proj.	0.0641	-0.0203	6.991
"	/cr.vol.	0.0073	0.3099	8.758
"	/cr.sf.a.	0.0119	-0.4670	11.254
control area				
vol.inc./g.b.h.		0.0453	-0.4511	17.323
"	/height	0.0374	-0.9280	5.964
"	/cr.proj.	0.0106	-0.0145	11.947
"	/cr.vol.	0.0013	0.0481	12.819
"	/cr.sf.a.	0.0023	-0.0913	16.389
b.a.inc./g.b.h.		0.2239	-2.3887	12.667
"	/height	0.1892	-4.8750	5.780
"	/cr.proj.	0.0526	-0.2329	10.033
"	/cr.vol.	0.0064	0.0765	10.713
"	/cr.sf.a.	0.0113	-0.6326	13.499

Whilst all values of 't' are significant at 0.1%, the greatest values appear in the regressions between increment and crown surface area, particularly in the thinned area, and lowest values appear in the increment/height regressions. High values of 't' are obtained for g.b.h regressions. With the exception of height, the regressions between increment and the remaining treevvariables show higher values of 't' in the control area.

Multiple regression analyses

To examine the effect of each of the above mentioned stand characteristics on increment when all others were held constant, multiple regression analysis was employed.

In addition to g.b.h., height, crown volume, crown projection and crown surface area, one other variable, an index of the competition between the selected trees and its neighbours, was used in the analysis. Multiple regression analysis was carried out separately for thinned and control areas, for each of basal area and volume increment and for four different indices of competition.

The competition indices used were selected after several preliminaryytests using mathematical models which incorporated the measurements taken for this purpose, described previously. It was possible to reject certain of these by comparing the computed indices of the thinned and control trees. For example the index of/

of Kennel (1964) which incorporates the crown diameter and height of competing trees, the height of the selected tree and the distance between them, produced figures which showed no regular difference between the thinned and control trees.

Three of the computed indices were eventually used. These were as follows.

index 1 - $\sum \frac{1000 \text{ x } gc/gs}{a^2}$

index 2 - $\sum \frac{gc \text{ x } k}{gs \text{ x } a^2}$

index 4 - $\frac{\sum \pi k^2(10 + k - a) - 32k^3/9 + c.f}{\pi(1000/3 - r^2(10 - r) - r^3/3)}$

(where a + k exceeds 10, then
$c.f = \pi k^2(a + k - 10)$, otherwise
c.f. = 0)

where gs = g.b.h. of selected tree

gc = g.b.h. of competing tree

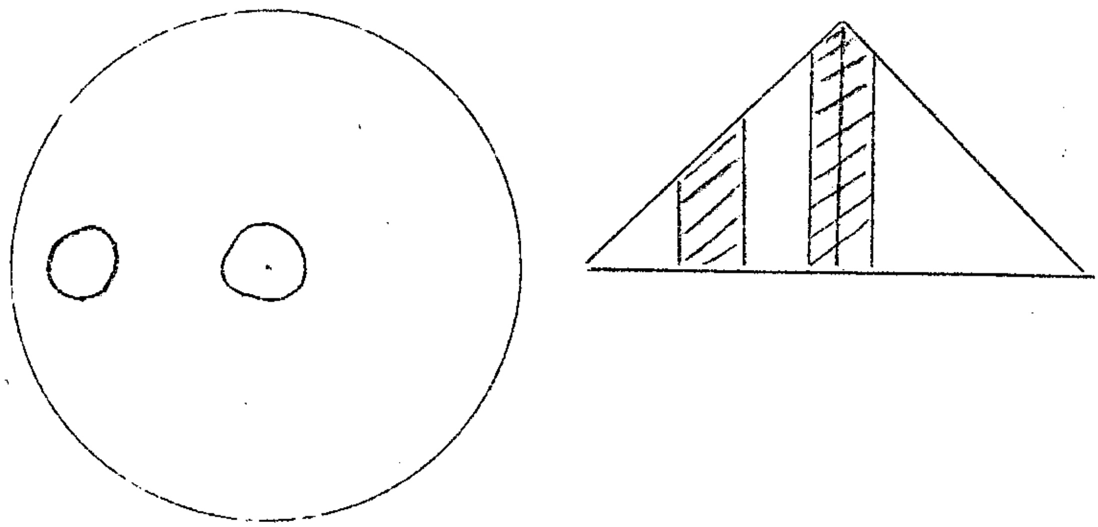
a = distance between competing and selected trees -ft.

r = crown radius of selected tree -ft.

k = crown radius of competing tree -ft.

c.f. = correction factor

Index 4 is dependent on the total crown projection of trees competing with the selected tree, i.e. within 10 feet of the selected tree, and the distance of each competing/



competing tree from the selected tree. Competition is taken to be directly proportional to distance, thus at ten feet from the selected tree a 'competing' tree has no effect. The Model can best be visualized as a cone of radius 10 feet and of height 10 feet. The volume of cone occupied by a tree within the 10 feet radius, is dependent on its crown projection and its position relative to the central axis, as shown in the diagram above. Index 4 is the ratio of the total volume occupied by competing trees to the volume of the cone minus that of the selected tree.

A fourth index (index 3) was obtained by making a count of competing trees with a wedge prism angle guage. (Jackson and Ure, 1964, and Warren, 1960) This is in effect a measure of the basal area of competing trees. Counts taken with a prism of factor 20 were used in the analysis. (The factor multiplied by the number of trees counted at any point gives the basal area in square feet.)

The results of the regression analyses are summarised below. The significance or otherwise of the variables in the regressions are indicated according to the usual convention.

Table 27.- Summary of multiple regression analyses

index number	g.b.h	height	crown vol.	crown proj.	crown s.a.	comp. index
basal area increment of released trees						
1.	x					$\underline{x}$
2.	x				x	
3.	x				x	
4.	x				x	
vol. inc.- released trees						
1.	x			$\underline{x}$		
2.	x					
3.	xx					
4.	xx					
b.a.inc. - control trees						
1.	x				x	
2.						
3.					x	
4.					x	
vol.inc. - control trees						
1.	xxx				x	
2.	xx					
3.	xx				x	
4.	xx				x	

N.B Significance at 5%, 1%, and 0.1% are shown by x, xx, and xxx respectively.
Negative associations are denoted by underlining.

Girth at breast height is on the whole most significantly and positively related to increment, more so in the volume increment analysis. Height and crown volume are not significantly related to increment. Although only once shown to be significant, crown projection is almost invariably negatively related to increment, appearing more so in the thinned trees. The most significant crown parameter is crown surface area which is positively related to increment. On one occasion only was the index of competition significant in the regressions. This is not unexpected considering the similarity of degree of competition within each area. Further multiple regression analyses were therefore carried out combining the data for both released and control trees.

These analyses are summarised below.

Table 28. - Multiple regression analyses of pooled data

index number	g.b.h	height	crown vol.	crown proj.	crown s.a	comp index
volume increment						
1.	xxx				xx	
2.	xxx				xxx	
3.	xxx				xx	x
4.	xxx				xxx	x
basal area increment						
1.	xx				xxx	x
2.	xx				xxx	x
3.	xxx				xxx	xx
4.	xx				xxx	xx

The significance levels shown in Table 28 are based on values of 't' for 53 degrees of freedom, as opposed 23 degrees of freedom for the previous analyses. (Table 27)

All four indices are shown to be significant in the basal area increment analyses. It is clear that indices 3 and 4 are the better measures of competition and are equally good.

....

The reason for g.b.h. being so strongly positively correlated with girth increment is not immediately clear, considering that all other factors are constant. The most likely explanation is that greater girth is an indication of the inherent genetic superiority of the tree. Secondly, it is not unlikely that a tree with greater stem diameter may have better developed roots and thus have an advantage in conducting materials from the soil. The third though least likely explanation rests with the greater area of cambial surface which accompanies greater girth. Possibly all of these factors are contributory to increment.

Though tree height is not significant when considered in isolation, it must be noted that other parameters of greater significance in themselves are dependent on height to some extent. The results of both linear and multiple regression analyses show that crown surface area is most closely related to increment. The negative relationship which is found between crown projection and volume increment, other factors being constant is an/

an indication that the most productive crowns, volumes being constant, are narrow crowns. As might be expected this is more apparent in the thinned area where the lower crowns of trees are functional.

There are many possible alternative expressions of competition to those used here. Undoubtedly these oould be further refined with repeated analysis. As far as the refinement process has been taken in this study, none of the computed indices is shown to be a better indicator of competition than the simple tree count provided by the wedge prisms, a measure which is very easily obtained.

(d) Increment per unit of crown projection

The average increments per unit of crown projection of those trees which constitute the girth categories given in Table 23 are shown below. Basal area increment is expressed in square inches per 1000 square feet of crown projection and volume increment in true cubic feet per 1000 square feet of crown projection.

Table 29. - Increment per unit of crown projection

Girth category	1	2	3	4
b.a. - thinned	80.80	87.00	70.14	40.21
b.a. - control	57.66	52.31	37.24	20.92
vol. - thinned	16.08	17.26	13.37	9.03
vol. - control	13.30	13.29	10.16	7.04

Table 29 shows that the efficiency of the third category of the thinned trees is greater than that of the first category of control trees. A second point which is noteworthy is that the efficiency of the second category of released trees exceeds that of the first category.

Owing largely to the fact that the selected trees were not taken entirely at random, i.e. without restrictive conditions, they are not representative of the plots as a whole and therefore comparison of total production in each is not possible.

Discussion

The results of the study into the relationship between g.b.h. and the length of growing season, closely agrees with a similar study by Kozlowski and Peterson (1962) who found that initiation of radial growth at bh in suppressed 34 year old red pine (*P.resinasa*) was later than in intermediate and dominant trees, and that suppressed trees subsequently had a shorter growing season.

This investigation supports the conclusions reached in earlier chapters on the relationship between increment and other variables. As in the literature, absolute increment was found to increase with increasing g.b.h., height, crown volume, crown projection, and crown surface area. Multiple regression analysis has further clarified the relationships by studying the effect of each in isolation.

isolation. The relationship between increment and crown projection endorse the findings of Kennel and Assmann, and in conjunction with the significance of crown surface area which emerged, the study has consolidated the hypothesis put forward in Chapter 3 that the most efficient crowns for a given volume are narrow crowns.

The effect of thinning on the efficiency of trees is very considerable. The most important result is that the third girth category of thinned stems, which may be roughly equated with sub-dominants, is more efficient than the first category, the dominants in the control area. The percentage increase in efficiency is greater with lower girth class, though even the highest category has shown a substantial increase in efficiency.

The thinned 'co-dominants' are more efficient than the dominants, a result which has been recorded by other workers in older stands.

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Summary

1. The following pairs of variables are highly significantly and positively related: height-g.b.h., height-crown projection, height-crown depth, height-crown volume, g.b.h.-crown projection, g.b.h.-crown depth, g.b.h-crown volume, crown projection-crown depth and crown projection-crown volume.

2. ~~Growth~~ Initiation and cessation diameter growth appears to occur earlier in trees of greater and smaller g.b.h. respectively. Small trees in the unthinned area appear to have a slightly shorter growing season than those released.

3. Growth rate reaches a maximum within 2-3 weeks of initiation and starts to fall off towards the end of July.

4. Where each of g.b.h., height, crown volume, crown projection and crown surface area increases, increment increases.

5. In the absence of the effect of all other factors, greater increment is associated with greater g.b.h., with greater crown surface area, and with smaller crown projection.

6. Released 'sub-dominants' are found to be more efficient than unreleased dominants in terms of increment per unit of crown projection.

7. Released 'codominants' are superior in these respects to released 'dominants'.

8. The efficiency of trees of all categories of g.b.h. has been raised by thinning, relatively more so in smaller trees.

9. Wedge prisms are effective instruments for measuring competition.

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Chapter 9.

General Discussion

It has been repeatedly shown that greater dominance is accompanied by greater absolute increment in an individual tree.

Of greater interest, however, is the increment produced per unit of space occupied by the tree, and crown projection has already been suggested as the most practical measure of growing space. It is evident from the literature reviewed, that as the crown projection increases, a point is reached when the increment per unit of crown projection decreases. This point would appear to have been reached by some of the trees in the Drumtochty experiment.

Assmann (1964) showed that the crowns of the trees in the D grade thinning plots at Bowmont, were less efficient than those of the B grade trees for the space they occupied, over the 1955-60 period. One tree of the D grade plot was shown to occupy six times the growing space of one tree of the B grade, but to have produced only four and half times the increment. (Assmann's "growing space" is the surface area of the upper portion of the crown, i.e. the upper two thirds of the crown height, assumed conical.) The average crown surface area/crown volume ratio was shown to be 1.45 and 3.14 in the D and B grades respectively. Assmann suggests that the relative rates of respiration and photosynthesis do not remain constant, but that certain sections/

sections of the crown are more active in one of these processes than the other. If one considers therefore that photosynthesis is mainly conducted, as Ladefoged suggested, in an outer sheath of crown, and that the central portion of the crown, largely due to light deficiency, respires more than it synthesises, then as the size of the crown increases the relative proportion of crown surface to crown volume decreases. This would presumably operate only after the crown had reached such proportions that a crown surface and a centre could be differentiated. It follows also from this that narrow crowns are more efficient on account of their relatively large surface area and small 'respiring central portion'.

Whether or not the above explanation is the correct one, the fact remains that crowns of large proportions can be inefficient. ~~remains.~~ One of the principles of the Scottish Eclectic thinning is to favour continually a certain number of selected stems in order to permit free crown development. Clearly this principle incurs the risk of production losses. Assmann's view that foresters are so impressed by the growth of large crowned trees, that they are blind to the possibility of loss of production, may well be true of those practising the Scottish Eclectic method of thinning.

The literature review suggested that lower branches were relatively less productive than the other parts of the crown. The leaf characteristics, low chlorophyll content/

content and high surface area/weight ratio of the foliage would suggest that here too the reason for low efficiency may be a relatively greater ratio of respiration to photosynthesis than elsewhere in the crown.

Lower canopy trees were noted by Burger and others to exhibit similar foliage to that of the lower crown in upper canopy trees. It is not unreasonable to expect that this foliage functions in a similar manner, which would explain the relative inefficiency which was noted in the literature. Bormann(1965) investigating the growth pattern of suppressed Pinus strobus in a 60 year old stand, suggested that as the tree received less solar energy by virtue of its position, its metabolic functions were such as to prolong its period of survival. This was based on his finding that whilst no xylem was being formed by the cambium, consequently no diameter growth was being recorded, yet foliage and more particularly terminal shoot growth was considerable, suggesting that investing photosynthate in the production of photosynthetic organs, whilst depending on conducting channels of previous years, was the best course for survival.

One additional factor of undoubted importance to the production of the individual is the length of its growing season. The results of the study by Kozlowski and Peterson are confirmed by the findings of the Drumtochty experiment.

The study of inter-class movements of trees in Chapter 7 was found to support the results of those papers reviewed in /

in Chapter 5. In both cases the absence of observations of movements of trees under very heavy crown thinning conditions is to be regretted. The discovery that the degree to which the upper canopy is opened affects the proportion of trees moving down through the classes is hardly surprising in itself. Of greater importance is the suggestion from the statistical analysis that no degree of thinning, which would be considered practical, in the upper canopy would arrest completely these downward movements. Far less would it induce upward movements in canopy class; nor is there any physiological explanation evident which would suggest that such treatment would in fact induce upward movements to occur. Upward movements appear in no way to be related to treatment and are much too rare to be of practical importance. Therefore, while it may be reasonable to expect an element of the lower canopy to persist as such under suitable conditions of light, it appears unreasonable to expect that such trees could improve their relative positions. Opposing views on this topic were mentioned in Chapter 1.

Whether or not heavy crown thinning is less productive than other types of thinning resolves itself into the question—Is the loss of increment which is incurred by the removal of a high proportion of the potentially greatest producers compensated by the increase in production induced in the remaining trees? This study cannot be expected to answer this question. Even an observation period of a full thinning cycle would leave room for doubt/

doubt, far less a study of one growing season. There can be no doubt, however that a vigorous response was obtained from the thinned trees in the Drumtochty experiment. The released 'sub-dominants' indeed are seen to be more efficient in terms of unit projection area than the unreleased dominants. Three points should be borne in mind when considering the results given in Table 29. Firstly, the control condition is not a practical treatment, and a low thinned plot would have made a valuable additional comparison. It was recorded, for example, in Chapter 7 that the removal of lower canopy elements increases the production of the upper canopy elements. Secondly, the increment of the released upper canopy elements still remains higher than those of the lower canopy which were similarly released. Thirdly, the results of the multiple regression analysis indicated that trees of greater g.b.h., other factors being constant, were better producers. By removing such trees, superior genotypes may be sacrificed.

Long term experiments in thinning method were reviewed in Chapter 6. The conclusion reached was that crown thinning was less productive than low thinning, this becoming more apparent towards the end of the rotation. The results of experiments in selection thinning were less conclusive. One experiment (Jack,1965) which was not discussed at that stage is perhaps more relevant to this investigation in that it covers a very short period and concerns Sitka spruce of about the same age (P43) as/

as the Drumtochty stand.

The experiment, in Northern Ireland, consists of two series of four thinning treatments, one at Cam, the other at Baronscourt. The treatments are described as, "Cam" thinning - a selection thinning very much akin to that used at Drumtochty, an "Eclectic" thinning - similar to the Scottish Eclectic method, a low thinning equvalent to C/D grade, and a control plot. The plots have been thinned once only, in April 1961. Table 30 shows the periodic annual increments of each plot from the time of thinning until December 1963.

Table 30. - P.A.I. of N.Ireland thinning plots, 6/61-12/63

Series	control	low	ecl.	"Cam"	mean
Cam	291	226	252	131	225
Baronscourt	303	305	219	227	263
means	297	276	236	179	

N.B. Units are Hoppus feet per acre.

The results clearly suggest that the heavier the crown thinning, the greater is the loss of production. Results over such a short period are inevitably liable to be contested, but the extent of the differences cannot be easily accounted for otherwise.

The most productive stand must be that composed of the maximum number of the most efficient individuals. On the basis of the findings of this thesis it may be thought that such a stand was one constituted by upper canopy/

canopy trees of deep, narrow crowns. The maintenance of deep crowns is dependent on the light conditions prevailing in the lower strata of the stand, which rests in turn with stand structure or density. As an inverse relationship exists between crown depth and density (Beekhuis, 1965) it follows that as productive capacity increases through increasing stocking, it is lowered at the same time by reduction in crown depth. When considering this conflict, the inefficiency of the lower crown must be noted, and it would seem not unlikely that maximum production would be obtained where the stand density was such as to eliminate that portion of the crown below the point of maximum diameter, i.e. Burger's "sun crown".

This concept of optimum stand structure is purely theoretical and is attended by numerous suppositions. In any event the formulation of an optimum stand structure is an immensely difficult task both in theory and in practice.

The principle tool at the forester's disposal, by which he can manipulate stand structure, is the practice of thinning. If in thinning it is desired to exploit the potential production of the stand to a greater degree, the following points are suggested by the work of this thesis.

(a) Thinning treatments which permit continual uninterupted development of the crown should be avoided. Narrow crowned trees should be favoured in selecting maincrop elements.

(b)/

(b) Subject to the conditions of (a), upper canopy trees are generally more efficient producers than those of the lower canopy. Trees which have become suppressed are inefficient producers irrespective of thinning treatment.

(c) Trees of equal height and crown dimension, but of greater g.b.h. appear to be superior producers worthy of retention.

(d) Upper canopy trees benefit from the removal of lower canopy trees.

In addition to these points this work has shown that while trees of the lower canopy may persist under adequate conditions of light, they cannot in practice be expected to advance to higher relative positions in the canopy.

In conclusion, the scope of this work requires reiteration. Its content is purely biological. Production is considered in terms of stem volume measurement, and experimental work has been confined to one genus. It is not unlikely that the merits that one method of thinning may have from a biological viewpoint may be outweighed by economic considerations.

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Appendix 1.

Individual tree data, Drumtochty, thinned area.

No.	vol. inc. c.ft.	b.a. inc. sq.ins.	g.b.h.	ht.	cr. rad.	cr. dpth.	comp.index 3.	comp.index 4.
1.	0.195	0.843	13.75	36	23	21	7	0.318
2.	0.161	0.807	11.87	34	22	18	5	0.263
3.	0.440	1.973	17.62	38	29	23	3	0.267
4.	0.278	1.376	14.26	35	25	19	2	0.259
5.	0.691	3.249	21.25	41	45	28	6	0.449
6.	0.347	1.758	18.75	35	42	22	3	0.413
7.	0.619	3.508	22.00	33	39	23	3	0.240
8.	0.070	0.303	10.50	27	25	12	7	0.507
9.	0.104	0.402	10.87	33	21	16	5	0.329
10.	0.578	2.807	19.37	39	51	23	5	0.387
11.	0.329	1.716	14.00	36	31	22	4	0.443
12.	0.155	0.927	14.00	24	30	12	3	0.260
13.	0.215	1.231	15.87	25	31	13	5	0.249
14.	0.079	0.370	11.37	26	24	12	5	0.351
15.	0.248	1.134	16.75	34	35	19	6	0.211
16.	0.101	0.485	10.75	32	24	17	8	0.372
17.	0.246	1.389	14.00	30	33	12	4	0.191
18.	0.058	0.123	11.00	27	20	12	8	0.246
19.	0.688	3.269	20.25	41	40	26	3	0.362
20.	0.125	0.685	12.87	27	25	13	3	0.304

21./

Individual tree data (contd.)

No.	vol. inc. c.ft.	b.a. inc. sq.ins.	g.b.h.	ht.	cr. rad.	cr. depth	comp.index 3.	4.
thinned area.								
21.	0.164	0.861	12.37	31	26	17	6	0.143
22.	0.441	2.340	16.87	36	33	15	6	0.212
23.	0.535	2.907	12.25	31	34	23	2	0.135
24.	0.339	1.790	16.20	34	33	23	5	0.171
25.	0.073	0.252	10.50	29	15	12	5	0.387
26.	0.402	2.025	18.37	35	26	18	6	0.197
27.	0.640	3.091	19.75	40	35	26	5	0.426
28.	0.109	0.613	11.87	32	24	19	6	0.378
29.	0.284	1.534	13.62	33	28	20	4	0.227
30.	0.599	3.222	16.87	41	38	26	4	0.172

....

No.	vol. inc. c.ft.	b.a. inc. sq.ins.	g.b.h.	ht.	cr. rad.	cr. depth	comp.index 3.	4.
control area								
41.	0.505	2.467	19.75	38	38	25	7	0.538
42.	0.112	0.520	11.12	32	22	19	6	0.444
43.	0.221	0.719	16.00	33	33	19	6	0.522
44.	0.611	2.568	24.50	36	50	23	8	0.577
45.	0.671	3.192	23.70	37	56	24	6	0.855
46.	0.115	0.417	13.00	30	27	14	7	0.613
47.	0.336	1.509	17.62	34	28	20	9	0.528
48.	0.207	0.777	16.12	30	27	18	13	0.568
49.	0.037	0.000	9.87	27	22	11	10	0.534
50.	0.056	0.037	11.75	27	20	10	9	0.420

Individual tree data. (contd.)

No.	vol. inc. c.ft.	b.a. inc. sq.ins.	g.b.h.	ht.	cr. rad.	cr. depth	comp.index 3	4
control area								
51.	0.253	0.998	17.75	33	30	18	8	0.401
52.	0.488	2.351	20.75	33	43	18	8	0.830
53.	0.128	0.561	12.00	32	23	16	8	0.733
54.	0.139	0.562	14.00	28	31	13	9	0.651
55.	0.251	1.025	15.50	35	28	22	10	0.721
56.	0.038	0.000	11.12	23	21	11	10	0.646
57.	0.065	0.189	10.75	29	22	16	8	1.163
58.	0.516	2.730	20.00	36	35	23	9	0.637
59.	0.443	2.148	17.87	35	36	23	8	0.875
60.	0.077	0.043	13.62	26	25	11	10	0.549
61.	0.027	0.000	8.87	27	15	14	10	0.509
62.	0.058	0.149	10.37	29	20	15	8	0.589
63.	0.121	0.510	13.25	24	20	10	10	0.444
64.	0.240	1.169	14.75	34	25	18	7	0.438
65.	0.184	0.699	15.00	32	28	15	10	0.368
66.	0.091	0.128	13.37	32	21	14	11	0.403
67.	0.312	1.596	17.00	30	39	15	8	0.635
68.	0.357	1.457	19.25	32	36	17	9	0.495
69.	0.197	0.735	14.75	36	28	21	11	0.456
70.	0.602	2.915	20.37	33	43	20	8	0.418

N.B. Volume increment refers to the whole stem and is expressed in true cubic feet.

Appendix 2.

Analysis of variance of multiple regression equations.

Each equation is numbered according to: the competition index used; whether the increment refers to basal area or volume increment; and according to the treatment. The regression equations for the released trees are given in numbers 1-8, the control area 9-16, and the equations for the pooled data 17-24.

No.	Incre.	Comp.I.	Source	D.F.	S.S.	M.S.	F.6
1.	vol.	1.	Regression	6	1.133	0.189	44.25
			Residual	23	0.098	0.004	
			Total	29	1.231		
2.	"	2.	Reg.	6	1.123	0.187	39.89
			Res.	23	0.108	0.005	
			Tot.	29	1.231		
3.	"	3.	Reg.	6	1.129	0.188	42.50
			Res.	23	0.102	0.004	
			Tot.	29	1.231		
4.	"	4.	Reg.	6	1.128	0.188	42.11
			Res.	23	0.103	0.004	
			Tot.	29	1.231		
5.	b.a.	1.	Reg.	6	29.243	4.874	35.41
			Res.	23	3.166	0.138	
			Tot.	29	32.409		

Analysis of variance of regression equations (contd.)

No.	Incre.	Comp.I.	Source	D.F.	S.S.	M.S.	F.
6.	b.a	2.	Reg.	6	28.792	4.799	30.51
			Res.	23	3.617	0.157	
			Tot.	29	32.409		
7.	b.a.	3.	Reg.	6	29.044	4.841	33.09
			Res.	23	3.365	0.146	
			Tot.	29	32.409		
8.	b.a.	4.	Reg.	6	29.048	4.841	33.13
			Res.	23	3.361	0.146	
			Tot.	29	32.409		
9.	vol.	1.	Reg.	6	1.035	0.172	87.24
			Res.	23	0.045	0.002	
			Tot.	29	1.080		
10.	"	2.	Reg.	6	1.034	0.172	85.02
			Res.	23	0.047	0.002	
			Tot.	29	1.080		
11.	"	3.	Reg.	6	1.033	0.172	84.29
			Res.	23	0.047	0.002	
			Tot.	29	1.080		
12.	"	4.	Reg.	6	1.033	0.172	84.42
			Res.	23	0.047	0.002	
			Tot.	29	1.080		
13.	b.a.	1.	Reg.	6	25.821	4.304	38.63
			Res.	23	2.563	0.111	
			Tot.	29	28.384		

Analysis of variance of regression equations (contd.)

No.	Incre.	Comp.I.	Source	D.F.	S.S.	M.S.	F.
14.	b.a.	2.	Reg.	6	25.823	4.303	38.65
			Res.	23	2.561	0.111	
			Tot.	29	28.384		
15.	"	3.	Reg.	6	25.792	4.299	38.15
			Res.	23	2.592	0.113	
			Tot.	29	28.384		
16.	"	4.	Reg.	6	25.788	4.298	38.08
			Res.	23	2.596	0.113	
			Tot.	29	28.384		
17.	vol	1.	Reg.	6	2.181	0.363	101.53
			Res.	53	0.190	0.004	
			Tot.	59	2.371		
18.	"	2.	Reg.	6	2.182	0.364	102.08
			Res.	53	0.189	0.004	
			Tot.	59	2.371		
19.	"	3.	Reg.	6	2.190	0.365	106.74
			Res.	53	0.181	0.003	
			Tot.	59	2.371		
20.	"	4.	Reg.	6	2.190	0.365	106.85
			Res.	53	0.181	0.003	
			Tot.	59	2.371		
21.	b.a.	1.	Reg.	6	57.162	9.527	69.25
			Res.	53	7.291	0.138	
			Tot.	59	64.453		

Analysis of variance of regression equations

No.	Incre.	Comp.I.	Source	D.F.	S.S.	M.S.	F.
22.	ba	2.	Reg.	6	57.054	9.509	68.11
			Res.	53	7.399	0.140	
			Tot.	59	64.453		
23.	b.a.	3.	Reg.	6	57.704	9.617	75.52
			Res.	53	6.749	0.127	
			Tot.	59	64.453		
24.	b.a.	4.	Reg.	6	57.392	9.565	71.80
			Res.	53	7.061	0.133	
			Tot.	59	64.453		

....

N.B. All values of F are significant at 0.1%.

Appendix 3.

Multiple regression equations

The regression equations are in the form:

Increment = a (constant)
+ b1 x g.b.h.
+ b2 x height
+ b3 x crown projection
+ b4 x crown volume
+ b5 x crown surface area
+ b6 x competition index

The values of the partial regression coefficients with their standard deviations and 't' values, and the constant a are tabulated below for each of the 24 equations.

Eq. No.	coeff. or constant	value	S.D.	value of 't' (23 d.f.)	level of signif.
1.	b1	0.0197	0.0071	2.7794	x
	b2	0.0099	0.0068	0.1271	
	b3	-0.0142	0.0067	2.1329	x
	b4	0.0015	0.0012	1.2062	
	b5	0.0011	0.0014	0.7673	
	b6	-0.1087	0.0594	1.8304	
	a	0.0057			
2.	b1	0.0207	0.0075	2.7586	x
	b2	-0.0037	0.0064	0.5748	
	b3	-0.0122	0.0070	1.7431	
	b4	0.0009	0.0012	0.6954	
	b5	0.0021	0.0013	1.6029	
	b6	-0.0186	0.0189	0.9816	
	a	-0.0554			
3.	b1	0.0221	0.0071	3.1314	xx
	b2	-0.0035	0.0061	0.5679	
	b3	-0.0105	0.0063	1.6684	
	b4	0.0006	0.0010	0.5861	
	b5	0.0023	0.0011	2.0305	
	b6	-0.0133	0.0086	1.5465	
	a	-0.0796			

Eq. No.	coeff. or constant	value	S.D.	value of 't' (23 d.f.)	level of signif.
4.	b1	0.0222	0.0071	3.1394	xx
	b2	-0.0042	0.0061	0.7181	
	b3	-0.0118	0.0065	1.8192	
	b4	0.0009	0.0011	0.8306	
	b5	0.0021	0.0012	1.7846	
	b6	-0.2146	0.1453	1.4767	
	a	-0.0497			
5.	b1	0.0896	0.0403	2.2208	x
	b2	-0.0174	0.0389	0.4468	
	b3	-0.0701	0.0379	1.8495	
	b4	0.0051	0.0069	0.7437	
	b5	0.0094	0.0082	1.1554	
	b6	-0.7187	0.3372	2.1314	x
	a	0.5740			
6.	b1	0.0970	0.0435	2.2281	x
	b2	-0.0484	0.0373	1.2972	
	b3	-0.0555	0.0405	1.3714	
	b4	0.0009	0.0073	0.1256	
	b5	0.0167	0.0078	2.1472	x
	b6	-0.1152	0.1095	1.0517	
	a	0.3132			
7.	b1	0.1054	0.0406	2.5870	x
	b2	-0.0467	0.0352	1.3257	
	b3	-0.0452	0.0363	1.2500	
	b4	-0.0006	0.0065	0.0964	
	b5	-0.0175	0.0065	2.6919	x
	b6	-0.0845	0.0495	1.7078	
	a	0.1726			
8.	b1	0.1061	0.0405	2.6181	x
	b2	-0.0519	0.0347	1.4959	
	b3	-0.0541	0.0371	1.4577	
	b4	0.0017	0.0066	0.2652	
	b5	0.0162	0.0068	2.3733	x
	b6	-1.4267	0.8316	1.7156	
	a	0.3902			

Eq. No.	coeff or constant	value	S.D.	value of't'	level of signif.
9.	b1	0.0285	0.0071	4.0213	xxx
	b2	-0.0063	0.0056	1.1246	
	b3	-0.0008	0.0033	0.2456	
	b4	-0.0004	0.0006	0.7553	
	b5	0.0022	0.0009	2.5776	x
	b6	0.0228	0.0256	0.8922	
	a	-0.2833			
10.	b1	0.0280	0.0083	3.3646	xxx
	b2	-0.0053	0.0064	0.8289	
	b3	-0.0008	0.0034	0.2343	
	b4	-0.0003	0.0006	0.5391	
	b5	0.0019	o.0010	1.9737	
	b6	0.0031	0.0067	0.4644	
	a	0.2529			
11.	b1	0.0252	0.0073	3.4638	xx
	b2	-0.0067	0.0057	1.1711	
	b3	-0.0006	0.0035	0.1808	
	b4	-0.0004	0.0006	0.6638	
	b5	0.0022	0.0009	2.3120	x
	b6	0.0006	0.0068	0.0913	
	a	0.1817			
12.	b1	0.0248	0.0069	3.5736	xx
	b2	-0.0070	0.0059	1.1933	
	b3	-0.0006	0.0034	0.1638	
	b4	-0.0004	0.0006	0.7004	
	b5	0.0022	0.0009	2.3769	x
	b6	-0.0137	-0.0566	0.2420	
	a	-0.1592			
13.	b1	0.1167	0.0532	2.1931	x
	b2	-0.0447	0.0423	1.0502	
	b3	0.0024	0.0251	0.0952	
	b4	0.0048	0.0043	1.1067	
	b5	0.0159	0.0065	2.4398	x
	b6	0.1075	0.1919	0.5601	
	a	-1.2424			

Eq. No.	coeff. or constant	value	S.D.	value of 't'	level of signif.
14.	b1	0.1257	0.0618	2.0344	
	b2	-0.0336	0.0475	0.7060	
	b3	0.0022	0.0251	0.0865	
	b4	-0.0039	0.0044	0.8961	
	b5	0.0135	0.0072	1.8715	
	b6	0.0283	0.0495	0.5731	
	a	-1.4314			
15.	b1	0.1085	0.0540	2.0101	
	b2	-0.0455	0.0426	1.0695	
	b3	0.0014	0.0261	0.0545	
	b4	-0.0043	0.0045	0.9587	
	b5	0.0148	0.0069	2.1421	x
	b6	-0.0113	0.0503	0.2253	
	a	0.6782			
16.	b1	0.1049	0.0517	2.0297	
	b2	-0.0450	0.0437	1.0291	
	b3	0.0024	0.0257	0.0931	
	b4	-0.0044	0.0044	1.0018	
	b5	0.0151	0.0069	2.1955	x
	b6	0.0458	0.4212	0.1087	
	a	0.8092			
17.	b1	0.0214	0.0048	(53 d.f.) 4.4194	xxx
	b2	-0.0029	0.0042	0.6976	
	b3	-0.0048	0.0033	1.4448	
	b4	0.0000	0.0006	0.0695	
	b5	0.0022	0.0007	2.9577	xxx
	b6	-0.0217	0.0162	1.3367	
	a7	-0.1630			
18.	b1	0.0209	0.0048	4.3033	xxx
	b2	-0.0041	0.0041	1.0003	
	b3	-0.0049	0.0033	1.4650	
	b4	-0.0000	0.0006	0.0514	
	b5	0.0024	0.0007	3.6031	xxx
	b6	-0.0057	0.0040	1.4351	
	a	-0.1521			
19.	b1	0.0247	0.0050	4.9596	xxx
	b2	-0.0028	0.0041	0.6785	
	b3	-0.0046	0.0032	1.4151	
	b4	0.0000	0.0005	0.0479	
	b5	0.0210	0.0007	3.0001	xx
	-b6	-0.0080	0.0035	2.0919	x
	a	0.1700			

Eq. No.	coeff. or constant	value	S.D.	value of t	level of signif.
20.	b1	0.0220	0.0047	4.6443	xxx
	b2	-0.0037	0.0040	0.9247	
	b3	-0.0041	0.0032	1.2798	
	b4	0.0000	0.0005	0.0789	
	b5	0.0024	0.0007	3.5872	xxx
	b6	-0.0836	0.0397	2.1050	x
	a	0.1700			
21.	b1	0.0825	0.0300	2.7462	xx
	b2	-0.0377	0.0260	1.4504	
	b3	-0.0229	0.0270	1.1084	
	b4	-0.0021	0.0036	0.5864	
	b5	0.0159	0.0046	3.4187	xxx
	b6	-0.2409	0.1006	2.3955	x
	a	-0.0118			
22.	b1	0.0774	0.0304	2.5483	x
	b2	-0.0507	0.0258	1.9665	
	b3	-0.0226	0.0209	1.0829	
	b4	-0.0031	0.0035	0.8967	
	b5	0.0188	0.0042	4.4273	xxx
	b6	-0.0550	0.0249	2.2085	x
	a	0.0229			
23	b1	0.1134	0.0304	3.7333	xxx
	b2	-0.0379	0.0249	1.5237	
	b3	-0.0196	0.0197	0.9930	
	b4	-0.0027	0.0033	0.7990	
	b5	0.0156	0.0043	3.6534	xxx
	b6	-0.0698	0.0216	3.2330	xx
	a	0.3073			
24	b1	0.0876	0.0296	2.9579	xx
	b2	-0.0437	0.0252	1.8754	
	b3	-0.0155	0.0202	0.7684	
	b4	-0.0035	0.0034	1.0446	
	b5	0.0189	0.0041	4.4894	xxx
	b6	-0.6859	0.2479	2.7661	xx
	a	-0.2860			

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Hamilton, G.J.
The Relationship between Increment and Dominance in Individual Trees as a Basis for Thinning Method.

M.Sc. Thesis, 1966.

ABSTRACT OF THESIS

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Degree M.Sc. *Date* 2nd November 1965

Title of Thesis The relationship between increment and dominance of individual trees as a basis for thinning method

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The thesis is in three parts; a literature review (summary on page 55); an analysis of Forestry Commission sample plots of L/C and C/D grade thinnings in spruce (summary on page 81); and a study of the increment of individual trees under different thinning treatments over one growing season,(summary on page 112).

Analysis of data from 9 Forestry Commission sample plots of L/C and C-D thinning grades where records of canopy class and girth at breast height were available over a period of 14-17 years showed that a net downward movement of trees between canopy classes took place with the development of the stand. Though no difference was apparent between treatments, it was found that the proportion of trees changing their status in this way was inversely related to the degree of canopy opening. Upward movements of trees were rare and were unrelated to treatment.

Increment studies in these plots showed that absolute increment per tree increased with dominance. Greater absolute increment was associated with the upper canopy elements of the C-D plots. No appreciable difference was found between the increment percentages of the sub-dominant classes in each treatment.

A field experiment conducted in 23 year old Sitka spruce, showed that absolute increment increased with dominance. Multiple regression analysis showed that increment was negatively related to crown projection, positively related to girth breast height and crown surface area, other factors being constant. (i.e. those mentioned plus crown volume, tree height, and competition) Thinning in the form of severe crown thinning increased the efficiency, i.e. increment per unit of crown projection, of sub-dominant trees such that they were equally efficient as unthinned dominants. The growing season was found to be greater in trees of the upper canopy. Wedge glass prisms were found to be effective instruments for measuring competitio

The conclusions reached with regard to thinning practice were; that narrow crowned trees and greater g.b.h., other factors being constant should be favoured as maincrop elements; that treatments encouraging excessive crown development should be avoided; that upper canopy elements are generally better producers and should be retained; and that removal of lower canopy elements has a significant favourable effect on the remaining trees of the upper canopy. These assume that maximum volume production is the aim of thinning, and which the literature suggests is not obtainable with crown thinning methods.

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